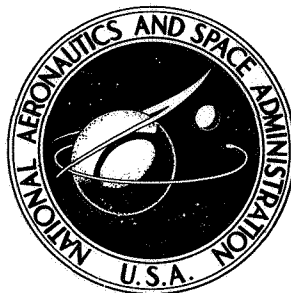


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PURGING OF MULTILAYER INSULATION BY GAS DIFFUSION

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PURGING OF MULTILAYER INSULATION BY GAS DIFFUSION

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SUMMARY

An experimental investigation was conducted to determine the time required to purge a multilayer insulation (MLI) panel with gaseous helium by means of gas diffusion to obtain a condensable (nitrogen) gas concentration of less than 1 percent within the panel. Two flat, rectangular MLI panel configurations, both constructed of 15 double-aluminized Mylar radiation shields separated by double silk net spacers, were each mounted in a purge box and tested. The first (or basic) MLI panel configuration was purged by exposing the panel edges along the two sides to helium purge gas. The second MLI panel configuration incorporated a butt joint through which the helium purge gas was forced to flow.

The purge technique relied on the flow of helium purge gas to reduce the condensable gas concentration at the edge or butt joint of an MLI panel and then on the diffusion of the helium purge gas into the panel to displace the condensable gas therein. The test results indicated that the rate at which the condensable gas concentration at the edge or at the butt joint of an MLI panel was reduced was a significant factor in the total time required to reduce the condensable gas concentration within the panel to less than 1 percent. The total purging time required, for example, for the MLI panel purged by flowing purge gas solely through the butt joint, varied from 245 minutes to 152 minutes for volumetric purge rates of 9.5 to 40.6 MLI panel volumes per hour, respectively.

The experimental data agreed well with analytical predictions made by using a simple, one-dimensional gas diffusion model in which the boundary conditions at the edge of the MLI panel were time dependent. The analytically determined value of the diffusion coefficient was used for the basic MLI panel. This value was increased by 30 percent for the MLI panel incorporating the butt joint to obtain a good correlation with the experimental results.

INTRODUCTION

The concept of using multilayer insulation (MLI) for the thermal protection of cryogenic propellants in space vehicles has been the subject of many experimental and analytical investigations for a number of years. One problem area still requiring additional investigation, however, is that of purging condensable gases (e.g., air, nitrogen, or water vapor) from within the multilayer insulation system before filling the propellant tanks with cryogenic propellants prior to launch. The freezing of condensable gases within the MLI or the presence of adsorbed molecules of water vapor on the surfaces of some insulation materials, particularly aluminized Mylar radiation shields and some spacer materials (e.g., silk netting as noted in ref. 1) can result in increased outgassing. Longer times are thus required to achieve low interstitial pressures between the radiation shields. The presence of water within the layers of multilayer insulation also tends to degrade the emissivity of the highly reflective surfaces, particularly aluminized surfaces. All these potential problems can degrade the thermal performance of MLI systems to varying degrees and for varying periods of time. However, any potential degradation must be eliminated, or at least minimized, if the insulation system is to provide predictable thermal performance for a given space flight (or for repeated use in several space flights for a MLI system installed on a fully reusable space vehicle).

Several of the previous investigations concerned specifically with purging of multilayer insulation systems are noted in references 2 to 5. It was shown that, at least for a small-scale, 66-centimeter (26-in.) diameter, test tank insulated and enclosed in a purge bag, the multilayer insulation could be purged so that less than 1 percent condensable gases remained within the layers (ref. 2). In these tests, gaseous helium was introduced underneath the multilayer insulation, which consisted of either double-aluminized Mylar or aluminum foil with glass paper spacers at a layer density of approximately 25 layers per centimeter (63 layers/in.). The mechanism by which the helium purge gas replaced the condensable gas (air) within the MLI panels was gas diffusion. The reduction of condensable gas to a concentration of less than 1 percent was achieved with less than 25 MLI panel purge volumes of gaseous helium at volumetric purge rates of approximately 15 and 30 MLI panel volumes per hour.

The work on MLI purge systems reported in reference 3 also proposed using a low gaseous helium volumetric purge rate (23 MLI panel volumes/hr) for a 2.67-meter- (105-in.-) diameter, liquid-hydrogen propellant tank that was insulated with 68 layers of double-aluminized Mylar and Dacron net spacers contained within a purge bag. It was predicted analytically that approximately 2 hours would be required to reduce the condensable gas concentration at the outlet of the purge bag to 1 percent or less. However, no indication of the time history of the condensable gas concentration within the MLI panels themselves was given. Unfortunately, this purge system was not tested experimentally to determine its actual performance.

The work reported in references 4 and 5 concentrated on MLI purge systems that would rapidly displace the condensable gas within an MLI panel by means of a relatively high-velocity purge gas flow laterally between the radiation shields rather than by gas diffusion. This purge technique used a low-layer-density MLI (Superfloc at approximately 12 layers/cm (30 layers/in.)) and a high gaseous helium volumetric purge rate (100 MLI panel volumes/hr) injected at three discrete points within each MLI panel by means of purge pins penetrating the insulation. Initial tests conducted on rather narrow, flat MLI panels indicated that the condensable gas concentration within a panel could be reduced to 1 percent or less within 5 minutes. Subsequent purge tests were conducted with a 2.23-meter- (87.6-in.-) diameter, oblate spheroidal, liquid-hydrogen tank completely insulated with 3.81-centimeter- (1.50-in.-) thick Superfloc MLI and enclosed in a purge bag. The purge test results indicated that a 1 percent condensable gas concentration at the outlet of the purge bag could be achieved within 5 minutes at, for example, a gaseous helium purge rate of about 218 MLI panel volumes per hour. The total helium usage was about 18.2 MLI panel volumes. However, there was no indication of the condensable gas concentration actually achieved within the MLI panels, the uniformity of the gas concentration throughout the MLI system, or the effect of the 1 percent remaining condensable gas concentration on the subsequent space-hold thermal performance of the MLI system.

This report presents experimental data and correlates them with analytical predictions to show the effectiveness of purging single, flat MLI panels with gaseous helium by means of gas diffusion. The gas diffusion technique was chosen for this investigation (1) because no maximum time limit for successfully purging the MLI was considered and (2) because no penetrations (purge pins) through the insulation panels are required to distribute the purge gas.

The MLI system tested was composed of double-aluminized Mylar separated by double silk net spacers. The thermal performance of this system has been studied extensively (e.g., refs. 1 and 6 to 8) and has been shown to provide predictable thermal performance. Two different MLI panels, one basic panel and one panel incorporating a butt joint, were tested to determine the time and purge gas usage required to achieve less than 1 percent condensable gas (nitrogen) concentration within an MLI panel. Various gaseous helium purge flow rates were used. Other test variables examined were (1) vertical (instead of the normal horizontal) orientation of the MLI panel and (2) the effect of allowing potential purge gas flow through the nylon grommets built into the MLI panel. The experimental data obtained were compared with analytical predictions that are based on standard equations for one-dimensional gas diffusion.

EXPERIMENTAL APPARATUS

Multilayer Insulation Panels

Two multilayer insulation panels, shown in figure 1, were fabricated for purge testing. Each of the two MLI panels consisted of 15 double-aluminized Mylar radiation shields alternately spaced with 16 double silk net spacers. A laminated aluminized Mylar/Dacron scrim cover sheet was applied to each side of the panel. The assembly of cover sheets, radiation shields, and silk net spacers was held together by nylon button-pin studs in rows spaced approximately 20.3 centimeters (8.0 in.) apart. Also incorporated into each panel were six nylon grommets, which were used in conjunction with nylon positioning pins to position and hold the MLI panel during testing. The construction of these MLI panels was modeled after existing MLI panels that had already been designed, fabricated, and installed on a cryogenic propellant tank located at the Lewis Research Center (ref. 8).

The first (or basic) MLI panel fabricated and tested for this investigation is shown in figure 1(a). The silk net for the spacers was used in the as-received condition directly from the roll. The resulting thickness of the MLI panel prior to installation of the nylon button-pin studs averaged 1.35 centimeters (0.53 in.). Because 0.95-centimeter- (0.38-in.-) long, nylon button-pin studs were used to assemble the MLI panel, its nominal thickness was also assumed to be 0.95 centimeter (0.38 in.) (a layer density of 17 layers/cm (43 layers/in.)).

The edges of the basic insulation panel in the lengthwise direction were left open so that the helium purge gas could diffuse between the individual radiation shields. The edges of the insulation panel at each end were sealed by cutting back the silk net and placing a 2.5-centimeter- (1-in.-) wide strip of double-backed tape, 0.051 centimeter (0.020 in.) thick, between adjacent aluminized Mylar radiation shields and cover sheets. After final trimming, the sealed edges of the completed MLI panel assembly were covered with aluminized Mylar tape. The fabrication technique provided an insulation panel that was to be purged from the edges along each side of the panel with a no-flow boundary existing along the centerline of the panel lengthwise. The nominal purge volume of the MLI panel was assumed to be 1.85×10^{-2} cubic meter (0.653 ft³).

The second MLI panel configuration (fig. 1(b)) was fabricated in a manner similar to the basic panel, with the following exceptions:

- (1) The 32 layers of silk net required for the MLI panel were cut to approximately the required size, stacked, sprayed with water, weighted down with a flat aluminum sheet, and allowed to dry. This procedure approximates that used for double-curved tank surfaces, where the silk net is placed on a male mold, sprayed with water, and allowed to dry to provide layers of silk net that conform to the contour of the tank surface. The resulting thickness of the completed MLI panel averaged 0.75 centimeter (0.30 in.)

(a layer density of 21.2 layers/cm (53.8 layers/in.)). The nominal purge volume of this MLI panel was then assumed to be 1.49×10^{-2} cubic meter (0.525 ft^3).

(2) The MLI panel was cut lengthwise to create a butt joint between the two sections of the panel 62.9 centimeters (24.8 in.) from one edge. The butt joint was overlapped with the aluminized Mylar/Dacron scrim cover sheet on both sides of the MLI panel and was secured with a hook and pile (Velcro) fastener, as shown in figure 1(b) and figure 2. This butt joint configuration between adjacent MLI panels is very similar to that used by the Lewis Research Center in the MLI systems installed on the cryogenic propellant tanks to be tested in other research programs (e.g., ref. 8).

(3) All four outside edges of the MLI panel were sealed with the combination of (1) double-backed tape between individual radiation shields and cover sheets and (2) aluminized Mylar tape covering the edges of the completed MLI panel assembly.

Purge Gas System

Each of the two MLI panels was installed and tested in a purge box, which is shown in figure 3. The inside dimensions of the purge box were 2.39 meters (7.83 ft) in length, 0.826 meter (2.71 ft) in width, and 3.89 centimeters (1.53 in.) in depth. The total volume of the purge box was 7.66×10^{-2} cubic meter (2.71 ft^3).

The basic MLI panel was simply laid in the purge box and held in place with the six nylon positioning pins bonded to the bottom of the purge box. The sealed ends of the MLI panel fitted snugly against the ends of the purge box. A gap of approximately 0.6 centimeter ($1/4$ in.) was left between each side of the purge box and the edge of the MLI panel to allow the purge gas to diffuse into the panel. The free volume of the purge box (total volume minus MLI panel volume) was assumed to be 5.81×10^{-2} cubic meter (2.05 ft^3).

The MLI panel with the butt joint was laid in the purge box, and the slight gap between the sealed edges of the panel and the inside of the purge box was bridged (and sealed) with aluminized Mylar tape. This ensured that all the purge gas introduced underneath the insulation panel would flow through the butt joint before being vented out of the purge box. The nylon grommet MLI penetrations were also sealed to prevent the flow of purge gas through these openings in the insulation panel for all but the last purge test conducted with this panel. The free volume of the purge box with this insulation panel was assumed to be 6.16×10^{-2} cubic meter (2.18 ft^3).

The purge gas system employed in the test program is shown in figure 4. Helium purge gas was introduced underneath the insulation panel through two 0.63-centimeter- (0.25-in.-) diameter purge tubes located 60 centimeters (24 in.) from each end of the purge box. Each purge tube contained 12 holes 0.033 centimeter (0.013 in.) in diameter to distribute the purge gas underneath the insulation panel. The free volume between the MLI panel and the top of the purge box could also be purged separately with a single

0.63-centimeter - (0.25-in. -) diameter purge tube. The purge gas flow rates underneath the MLI panel (MLI panel purge) and into the free volume of the purge box (purge-box purge) were measured separately by means of two rotameters. A separate nitrogen purge gas supply was provided to purge the insulation panel and purge box prior to each gaseous helium purge test.

Gas Sampling System

Six gas sampling tubes were provided to withdraw samples of purge gas, as shown in figure 4. One tube was used to obtain samples of purge gas at the edge of an MLI panel to determine the time-dependent boundary conditions needed as an input in order to obtain a solution of the analytical model. These purge gas samples were obtained exactly at the edge of the basic MLI panel and exactly at the butt joint of the second MLI panel. The other five gas sampling tubes were used to obtain samples of purge gas from within the MLI panel (between the radiation shields) at various locations. The portion of the sampling tubes located within an MLI panel was fabricated of 0.102-centimeter - (0.040-in. -) diameter stainless steel in order to minimize any disturbance to the MLI panel.

The gaseous helium/nitrogen concentration from each individual gas sampling tube was sensed by a commercial thermal conductivity cell normally used for chromatography and process gas analysis. The thermal conductivity cell used in this program had two glass bead thermistors to sense the difference in thermal conductivity of the sample gas flow as compared with a reference helium gas flow. The thermal conductivity cell was immersed in an ice bath to provide a relatively constant temperature environment. The thermal conductivity cell was connected to the six MLI gas sampling probes as shown in the flow schematic of figure 5. (Fig. 6 shows the flow-control panel.) The gas sample from each sampling tube was drawn through the sample side of the thermal conductivity cell by manipulating the toggle valves manually. Small-diameter tubing (0.069-cm (0.027-in.) inside diameter) and valves having a small internal volume were used throughout the gas sampling system, up to the needle valves, in order to minimize the time response of the flow system. This made it possible to withdraw only a small volume of purge gas from within the MLI panel so that the experimentally measured gas concentration would not be significantly affected by previous samples of gas withdrawn. Also small-diameter tubing of approximately equal lengths was used for the gas sampling tubes to provide for equal gas flow rates through all six tubes for a given gas concentration.

The gaseous helium for the reference side of the thermal conductivity cell, as well as known mixtures of gaseous helium and nitrogen for calibration purposes, was supplied from standard "K" bottles. These bottles are shown as a part of the gas calibration

system (fig. 5). These gases were supplied to the gas sampling system at pressures just slightly greater than 1 atmosphere to duplicate the pressure in the purge box during a purge test. The low-cracking-pressure check valves acted as pressure-relief valves to vent gas flow from the 'K' bottles that was in excess of the flow through the thermal conductivity cell. This flow was initially set at the desired value by adjustment of the downstream needle valve. The check valves had a nominal cracking pressure of 0.1 N/cm^2 (0.15 psi) and provided a relatively constant upstream pressure of $0.09 \pm 0.01 \text{ N/cm}^2$ (0.13 ± 0.015 psi) gage. The 3.66-meter - (12.0-ft-) long, small-diameter tubing provided a pressure drop in the gas calibration flow system that was approximately the same as that provided by the tubing in the MLI gas sampling system.

The electrical output signal from the thermal conductivity cell was visually read on a digital voltmeter and was also recorded on a strip chart.

Instrumentation

The thermal conductivity cell was the primary instrumentation for this investigation. Periodic calibrations of the cell were made throughout the test program by using known mixtures of gaseous helium and nitrogen as determined by an analytical mass spectrometer. The calibration curve for the instrument reading θ is shown in figure 7. The instrument provided relatively poor sensitivity to variations in gaseous nitrogen concentrations above 40 percent. But it did provide good sensitivity, as well as a nearly linear calibration, for gaseous nitrogen concentrations below 20 percent, which was the range of primary interest.

The maximum error in determining the gaseous nitrogen concentration under steady-state conditions is noted in figure 8. The data points indicate the maximum deviation from the nominal calibration curve that resulted from instrumentation drift during several steady-state calibrations. Although some drift of the zero and full-scale outputs of the instrument was noted during the steady-state calibrations and transient data taking, this effect was minimized by zeroing and spanning the output frequently while flowing helium and nitrogen, respectively, through the sample side of the thermal conductivity cell. In general, the error due to drift that was expected to occur in the purge tests was less than 3 percent while measuring gaseous nitrogen concentrations near 100 percent and was approximately 0.3 percent or less while measuring concentrations near 0 percent.

The overall time response of the thermal conductivity cell under transient gas concentration conditions necessarily includes the time response of the flow system. The overall time response for a step change in gas concentration was investigated during the calibration of the instrument. It was noted that the overall time response included an initial dead time t_d of approximately 0.23 minute, which represents the initial time

required to purge the volume of the flow system upstream of the thermal conductivity cell. This dead time was followed by a change in the instrument reading θ to a new value in a manner typical of a critically damped, second-order system. The response of the instrument reading for two different initial and final gaseous nitrogen concentrations is compared with the theoretical response in figure 9, where θ_I is the initial instrument reading and θ_F is the final instrument reading. The experimental data compare favorably with the theoretical curve for the assumed time constant τ of 0.0855 minute.

The total lag time t_ℓ of the response of the instrument to a linear change in gas concentration, such as would be present in an insulation panel during a purge test, would be $t_\ell = t_d + 2\tau$, or approximately 0.40 minute for the assumed time constant of 0.0855 minute. The dynamic error $(Kt_d + 2K\tau)$ occurring during a linear change K in the gaseous nitrogen concentration of 0.05 percent per minute, for example, would be approximately 0.02 percent. The change in gaseous nitrogen concentration of 0.05 percent per minute is of interest because this was the approximate rate of change within the MLI panel as the concentration was approaching 1 percent gaseous nitrogen. The gas flow through the thermal conductivity cell was continued for at least 1 minute for each gas sampling tube while experimental data were taken. Therefore, the dynamic error was small compared to the anticipated error due to drift, and no corrections for instrument error due to dynamic response were applied to the experimental data.

Other instrumentation included pressure and temperature transducers, which were used in conjunction with four rotameters (figs. 4 and 5) to determine gaseous helium flow rates through both the sample and reference sides of the thermal conductivity cell as well as through the purge system for the MLI panel and purge box.

TEST PROCEDURE

Prior to the start of each gaseous helium purge test, the MLI panel and purge box were thoroughly purged with gaseous nitrogen for several hours. The gaseous helium flow rate through both the sample and reference sides of the thermal conductivity cell were set at 13.8 ± 0.2 standard cubic centimeters per minute (0.842 ± 0.012 std in.³/min). Gas samples were then taken from within the MLI panel to confirm the presence of nearly 100 percent nitrogen. The helium purge rates for the MLI panel and purge box were set at the desired values at the start of the purge test and monitored intermittently thereafter. Purge gas samples were withdrawn for 1 minute each through the six gas sampling tubes at regular intervals during the purge test. These intervals were generally 1/2 hour. However, the intervals were extended to as long as 2 hours in some cases to determine if the volume of purge gas withdrawn from the insulation panel affected subsequent data. In most cases, the purge test was continued until it was determined that the

nitrogen concentration within the MLI panel had been reduced to less than 1 percent. Because of the time involved and the limited quantities of gaseous helium available, no attempt was made to experimentally determine the minimum nitrogen concentration that might be obtained within the MLI panel.

RESULTS AND DISCUSSION

Basic Multilayer Insulation

The purpose of the three (essentially identical) helium purge tests conducted with the basic MLI panel was to experimentally determine the purge characteristics of a simple, one-dimensional, gas diffusion purge technique for direct comparison with the analytical model noted in the appendix. The intent was to establish a nearly 100-percent-helium concentration (boundary condition) at both open edges of the horizontally oriented MLI panel as quickly as possible and then to monitor the resulting changes in gas concentration within the panel. The flow path of the helium purge gas for these three tests with the basic MLI panel is shown in figure 10, as well as the six locations at which the gas samples were withdrawn from within and at the edge of the insulation panel. A helium purge rate of approximately 20 MLI panel and purge-box free volumes per hour was arbitrarily selected for all three tests. In order to conserve helium usage, the purge rate was reduced (table I, tests 1A to 1C) when the gas concentration at the edge of the MLI panel had reached approximately 1 percent nitrogen. This reduction of the purge gas flow rate had little if any noticeable effect on the subsequent purge gas concentration measured at the edge of the MLI panel.

Results for the first test (test 1A) are shown in figure 11. The gaseous nitrogen concentration at the edge of the MLI panel (the boundary condition) decreased to 1 percent 77 minutes after the start of the test. Approximately 115 minutes, on the average, were required for the purge gas within the MLI panel to reach a nitrogen concentration of 1 percent. At no time during the purge test did there appear to be a significant dependency of the purge gas concentration upon the distance from the edge of the panel for the two distances examined.

The gaseous nitrogen concentrations at the edge of the MLI panel for the first three purge tests (tests 1A to 1C) are compared in figure 12. Although the concentrations were not identical for all three tests, they were sufficiently close that the data could be characterized by a single curve. The curve fit (faired curve) shown in figure 12 was used in the analytical prediction of the purge gas concentration within the MLI panel. The equation for this curve fit, as well as those for curve fits of subsequent tests, is noted in table II.

Effect of gas sampling rate. - The experimental data for the gaseous nitrogen concentration at the centerline of the basic MLI panel for these first three tests are shown in figure 13. Gas samples were withdrawn approximately every 15 to 20 minutes for test 1A, every 30 minutes for test 1B, and every 60 minutes for test 1C. Very little effect of the gas sampling rate can be noted until the nitrogen concentration approached 1 percent. Even at gas concentrations of less than 1 percent, the effect of the gas sampling rate was not significant considering the anticipated error of the thermal conductivity cell. All three sets of data can be characterized by a single analytical curve, as were the boundary conditions at the edge of the MLI panel (fig. 12).

Analytical correlation. - The gas concentration within the MLI panel at the centerline was predicted analytically by using the one-dimensional gas diffusion model presented in the appendix and the time-dependent boundary condition (curve fit) previously shown in figure 12. The resulting analytical prediction is shown as the solid curve in figure 13. The analytical model provided a very good correlation with the experimental data. The diffusion coefficient ($D_{AB} = 4.12 \times 10^{-3} \text{ m}^2/\text{min}$ ($4.43 \times 10^{-2} \text{ ft}^2/\text{min}$)) was the value obtained from the recommended equation (ref. 9) for the binary diffusion of two gases (in this case, helium (gas A) and nitrogen (gas B)). Also shown in figure 13 is the analytical prediction of the gaseous nitrogen concentration at the centerline of the panel for the case where the purge gas concentration at the edge of the panel was assumed to be 100 percent helium starting at time zero. A minimum of 79 minutes would be required to purge the MLI panel to 1 percent nitrogen concentration under ideal conditions (dashed curve.) And, for these tests, an additional 48 minutes were required because of the time-dependent boundary conditions (solid curve). Therefore, the rate at which the condensable gas concentration at the edge of the MLI panel is reduced is a significant factor in the total time required to reduce the condensable gas concentration within the MLI panel.

The actual time and the total volume of helium purge gas required to achieve 1 percent gaseous nitrogen concentration within the MLI panel are also shown in table I. For tests 1B and 1C, approximately 2 standard cubic meters (71 std ft³), or about 26 total purge volumes, of gaseous helium were required.

Multilayer Insulation Panel With Butt Joint

A second series of helium purge tests was conducted to experimentally determine (1) how rapidly a multilayer insulation panel incorporating a butt joint could be purged to less than 1 percent gaseous nitrogen concentration and (2) the effect of purge gas flow rate on the resulting purge time and gaseous helium usage required. The helium purge gas was introduced both into the free volume of the purge box and underneath the MLI panel in the first five purge tests and only underneath the MLI panel in the remaining tests. In addition, the correlation of the experimental data with the analytical model was

also of concern. The boundary conditions needed for the analytical model were not determined at the outside edges of the MLI panel assembly, as in the first series of tests, but rather at the butt joint between the two adjacent segments of the panel. This would be more representative of the actual insulation system configuration with several MLI panels, with the edges butted together, mounted on a propellant tank.

The flow path of the helium purge gas for this series of tests of the MLI panel with the butt joint is shown in figure 14, as well as the six locations at which the gas samples were withdrawn from within or at the butt joint of the insulation panel. All the helium purge gas introduced underneath the MLI panel had to flow through the butt joint (located 62.9 cm (24.8 in.) from the farthest sealed edge of the panel, fig. 1) before flowing into the free volume in the purge box and then venting from the purge box entirely. The helium purge rates for this series of tests (tests 2A to 2L) are shown in table I.

The experimental test results for the gaseous nitrogen concentration at the butt joint (boundary condition) and within the MLI panel are shown in figure 15 for test 2A. This initial test was conducted with a total helium purge rate of approximately 5 volumes per hour. Although the test was not continued as long as would have been required to achieve the desired 1 percent gaseous nitrogen concentration within the MLI panel, it was representative of the subsequent tests in this series. Very little variation in the purge gas concentration was found between the gas sampling locations 41.9 and 60.3 centimeters (16.5 and 23.8 in.) away from the butt joint.

Effect of total purge gas flow rate. - In tests 2B to 2D the total purge gas flow rate was varied in order to make a comparison with the results of test 2A. The gaseous nitrogen concentrations at the butt joint of the MLI panel (boundary conditions) for tests 2A to 2D are shown in figure 16. The total helium purge-gas flow rate was increased from 4.9 to 20.7 volumes per hour, 0.38 to 1.59 std m³/hr (13 to 56 std ft³/hr) for this test series. The volumetric purge rates for the MLI panel and the free volume of the purge box were maintained at approximately a 1-to-1 ratio (table I). Test 2C was a repeat of test 2B to check the repeatability of the test results.

The gaseous nitrogen concentrations within the MLI panel for tests 2A to 2D are shown in figure 17. A distinct, well-defined curve of the gaseous nitrogen concentration was observed for each of the three volumetric purge rates tested. The repeatability of the test results for tests 2B to 2C was excellent. Gas samples were withdrawn from the MLI panel every 30 minutes for test 2B and approximately every 60 minutes for test 2C. Again no significant dependency of the gas concentration on either the sampling rate or the distance of the sampling point from the butt joint (test 2D) was noted. The increasing volumetric gaseous helium purge rates resulted in less time required to achieve 1 percent nitrogen concentration within the MLI panel but also resulted in a requirement for larger total quantities of helium, as can be seen in table I.

Effect of purge-box purge gas flow rate. - For the next two tests (tests 2E and 2F) the volumetric purge rate in the free volume of the purge box was reduced to 4.8 and 0

volumes per hour, respectively, while the volumetric purge rate of the MLI panel was maintained at approximately 20 volumes per hour. The resulting boundary conditions at the butt joint are compared in figure 18 with the results from test 2D. No significant differences among any of these tests can be noted. The curve faired through the experimental data represents the time-dependent boundary condition for this MLI panel configuration. This curve was used as an input for the analytical prediction of the gaseous nitrogen concentration within the MLI panel. The gaseous nitrogen concentration representing the boundary condition decreased more slowly for this MLI panel configuration than it had for the basic MLI panel configuration (tests 1A to 1C), even when the total purge rates were approximately the same.

The experimental data for the gaseous nitrogen concentration within the MLI panel are shown in figure 19 for tests 2D to 2F. The experimental data showed no significant differences in the nitrogen concentration among all three tests, which might be expected since the boundary conditions were essentially the same. It appears then that the primary effect is produced by the purge gas being introduced underneath the insulation panel. The resulting decrease in the total volume of gaseous helium required to purge the MLI panel to 1 percent nitrogen concentration was from 4.90 to 1.00 standard cubic meter (173 to 35.4 std ft³) for these three tests (table I). The experimental data also showed a more rapid decrease in nitrogen concentration than those predicted analytically with the diffusion coefficient $D_{AB} = 4.12 \times 10^{-3}$ square meter per minute (4.43×10^{-2} ft²/min) used previously. Increasing the diffusion coefficient to 5.30×10^{-3} square meter per minute (5.70×10^{-2} ft²/min) produced good agreement between the experimental and analytical results. The reason for a somewhat faster decrease in the gaseous nitrogen concentration than would ordinarily be predicted is not apparent, unless the flow of helium purge gas through the closely spaced edges of the MLI panel at the butt joint provided some pumping action on the gas within the MLI panel. The analytical prediction for the basic MLI panel (tests 1A to 1C) is also shown in figure 19 for comparison. The gaseous nitrogen concentration within the basic MLI panel decreased more rapidly primarily because the nitrogen concentration at the edge of the panel, representing the boundary condition, had also decreased more rapidly.

Effect of MLI panel purge gas flow rate. - Tests 2G to 2J were conducted to vary the MLI panel purge gas flow rates for comparison with the results from test 2F. The volumetric purge rate was varied from 9.5 to 40.6 MLI panel volumes per hour for tests 2F to 2J, as noted in table I. Test 2J was a repeat of test 2I to again check the repeatability of the experimental data. The resulting boundary conditions for this group of tests are shown in figure 20. Each helium purge flow rate produced a distinct curve for the corresponding boundary condition. The curves faired through the experimental data were again used as input for the analytical prediction of the gaseous nitrogen concentration within the MLI panel. The use of a diffusion coefficient of 5.30×10^{-3} square meter per minute (5.70×10^{-2} ft²/min) provided a good correlation between the experimental data and the

analytical prediction for this series of tests, as shown in figure 21. This diffusion coefficient was used because it had previously provided a good correlation between experiment and analytical results for tests 2D to 2F (fig. 19). The repeatability of the experimental data between tests 2I and 2J was also very good. The purge gas sampling rate was every 30 minutes for test 2I; for test 2J it was basically every 2 hours.

The total helium usage to obtain 1 percent nitrogen concentration within the MLI panel decreased to 0.57 standard cubic meter (20.2 std ft³) at a volumetric purge rate of 9.5 MLI panel volumes per hour, with a corresponding increase in the time required to 245 minutes (table I). The gaseous helium usage (in terms of MLI panel volumes) for these tests as a function of the volumetric purge rate is shown in figure 22. The results indicate a nonlinear relation, with the required volume of purge gas approaching perhaps some finite limit as the purge rate is increased. The resulting time required to achieve a 1 percent gaseous nitrogen concentration within the MLI panel is shown in figure 23 as a function of the MLI panel volumetric purge rate. These results indicate a continually decreasing time requirement as the purge rate is increased, with good agreement between the analytical model and experimental test results.

Effect of vertical orientation. - Test 2K was conducted with the MLI panel oriented in a vertical position with gas sampling tube 1 located near the bottom of the panel. The insulation panel was purged at a volumetric flow rate of 9.5 MLI panel volumes per hour. In addition, only the vent at the bottom of the purge box was left open so that the gaseous helium purging of the MLI panel was aided by the buoyancy of the helium. The experimental test results for the gaseous nitrogen concentration at the butt joint and within the MLI panel are shown in figures 24 and 25, respectively. The gas sampling tube at the butt joint (gas sampling tube 1) was used to determine the boundary condition. It was located 27.3 centimeters (10.7 in.) from the bottom edge of the panel. As might be expected, the nitrogen concentration at the boundary (fig. 24) decreased more slowly at first and then more rapidly for the vertical orientation than for the horizontal orientation because of buoyancy effects. The nitrogen concentration within the MLI panel also decreased more rapidly with the panel in a vertical orientation, as shown in figure 25, with the top of the panel undergoing a faster decrease than the bottom of the panel. Therefore, it appears that the purging of horizontal sections of multilayer insulation will, in general, be more critical than the purging of bottom-vented vertical sections and will take longer periods of time.

The time required to reach a nitrogen concentration of 1 percent at the bottom of the MLI panel was estimated from the experimental data presented in figure 26. The data obtained from figure 25 from the sampling tubes located 60.3 centimeters (23.8 in.) from the butt joint are presented as a function of the vertical tube location. It appears that approximately 226 minutes were required to achieve a 1 percent nitrogen concentration at the bottom of the panel. The resulting total helium usage would then be approximately 0.53 standard cubic meter (18.7 std ft³) (table I).

Effect of uncovering grommets. - The final test (test 2L) was again conducted with the MLI panel oriented in a horizontal position. But in this test, pieces of aluminized Mylar tape, which had been covering the nylon positioning grommets to prevent helium purge gas from flowing through the grommets rather than just through the butt joint, were removed. The grommets and the butt joint were then parallel flow paths. The purpose of this test was to determine if significant quantities of purge gas would flow through the grommets, thereby changing the purge characteristics previously obtained. A volumetric purge rate of 9.5 MLI panel volumes per hour was used. The experimental results for the nitrogen concentration at the boundary and within the MLI panel are compared in figures 27 and 28, respectively, with the results obtained from tests 2I to 2J. However, as shown in the figures, no significant variations in the purge characteristics were observed.

CONCLUDING REMARKS

There are still some additional areas of work which must be experimentally investigated before the concept of purge multilayer insulation, in general, and the gas diffusion technique of purging multilayer insulation, specifically, can be considered ready for application to a spacecraft that uses cryogenic propellants. These areas include

1. Assessment as to whether reducing the condensable gas concentration within a multilayer insulation system to 1 percent is sufficient for satisfactory thermal performance in a subsequent space-hold environment
2. Determination of the time required to purge a multilayer insulation system mounted on a cryogenic propellant tank by means of gas diffusion to reduce the condensable gas concentration to 1 percent or less
3. Determination of the necessity for purging an MLI system with hot (340 to 395 K (612° to 711° R)) purge gas to remove absorbed water vapor

SUMMARY OF RESULTS

An experimental investigation was conducted (1) to determine if a multilayer insulation (MLI) panel could be purged with gaseous helium by means of gas diffusion to obtain condensable gas (i. e. , gaseous nitrogen) concentrations of less than 1 percent and (2) to provide data that could be correlated with a simple, one-dimensional gas diffusion model. The insulation system used in this investigation was composed of alternating double-aluminized Mylar radiation shields and double silk net spacers with a laminated aluminized Mylar/Dacron scrim cover sheet on each side of the assembled panel. Two MLI panel configurations were tested. The first (or basic) MLI panel was purged by exposing

the edges of the panel to gaseous helium. The second MLI panel incorporated a butt joint through which all of the helium purge gas introduced underneath the MLI panel was forced to flow. The following results were obtained:

1. It is possible to effectively purge multilayer insulation panels of a condensable gas (nitrogen) by means of gas diffusion with helium as the purge gas. The rate at which the nitrogen concentration in the MLI panel is reduced is determined as much by the ability to reduce the nitrogen concentration at the boundary (edge of the MLI panel or butt joint) as by the diffusion process itself. Gaseous nitrogen concentrations in the MLI panels of less than 1 percent were obtained within a period of approximately 4 hours or less.

2. For the basic MLI panel tested, the analytical predictions agreed very well with the experimentally determined reductions of nitrogen concentration within the MLI panel as a function of time. The diffusion coefficient used was calculated from standard equations for determining the binary diffusion coefficient for helium and nitrogen. The calculated value of the diffusion coefficient was 4.12×10^{-3} square meter per minute (4.43×10^{-2} ft²/min).

3. The MLI panel with the butt joint exhibited slower reductions in gaseous nitrogen concentration at the boundary than did the basic MLI panel under the same volumetric purge rates.

4. For the MLI panel with the butt joint, the analytical predictions agreed very well with the experimentally determined reductions in nitrogen concentration as a function of time if the value of the diffusion coefficient was increased to 5.30×10^{-3} square meter per minute (5.70×10^{-2} ft²/min).

5. The times required to achieve 1 percent nitrogen concentrations within the MLI panels varied from 115 to 280 minutes. The most efficient way (least helium usage) of purging the MLI panel with the butt joint for this investigation, where the MLI panel was enclosed in a purge box, was to introduce the helium purge gas only underneath the insulation panel. For this purge technique at a purge rate of 9.5 MLI panel volumes per hour, a total of 39 MLI panel volumes of helium over a period of 247 minutes was required to reduce the nitrogen concentration within the MLI panel to 1 percent. This time could be reduced to 152 minutes by purging at the rate of 40.6 MLI panel volumes per hour; however, a total of 103 MLI panel volumes of helium would be required.

6. Purging the MLI panel with the butt joint was accomplished slightly faster with the panel in a vertical orientation (and the purge box vented at the bottom) than in a horizontal orientation under the same helium purge flow rates.

7. The technique of withdrawing small samples of gas from the MLI panels to determine the gas concentration was adequate for this investigation. Varying the sampling rate during repeatable test conditions indicated that the withdrawal of a small sample of

gas from a given location within the MLI panel did not significantly affect the concentration of subsequent gas samples withdrawn from the same location for sampling rates from every 15 to 20 minutes to every 2 hours.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 23, 1975,
506-21.

APPENDIX - ONE-DIMENSIONAL GAS DIFFUSION IN

FLAT MULTILAYER INSULATION PANELS

It was assumed for this analysis that a flat multilayer insulation (MLI) panel was constructed such that the edges at each end of the panel were sealed and that no flow of purge gas would be permitted across this boundary. The edges of the panel along each side were considered to be open so that purge gases could flow across these boundaries as noted in figure 29(a). It was assumed that the MLI panel is initially filled with gaseous nitrogen and that the edges of the panel are exposed to a mixture of gaseous nitrogen and helium whose composition is time dependent (i.e., the gas at the boundary is initially nitrogen whose concentration decreases with time until the gas at the boundary becomes pure helium). A time-independent condition of pure helium was assumed at the boundary, and then Duhamel's superposition integral was used to obtain the solution for the time-dependent boundary condition.

The binary diffusion equation for the molar concentration of two gases, in vector form, is

$$\frac{\partial C_A}{\partial t} + (\nabla C_A \vec{v}^*) = (\nabla C D_{AB} \nabla M_A) + R_A \quad (1)$$

where

C_A molar density of gas A

t time

C molar density of the mixture of gases (AB)

D_{AB} diffusion coefficient of gases A and B

M_A mole fraction of gas A, C_A/C

R_A moles of gas A produced by chemical reaction per unit time

and

\vec{v}^* local molar average velocity,

$$\vec{v}^* = \frac{\sum_{i=1}^n C_i \vec{v}_i}{\sum_{i=1}^n C_i} = \frac{\sum_{i=1}^n \vec{N}_i}{\sum_{i=1}^n C_i}$$

where

n number of species of gas considered, 2

C_i molar density of species i

\vec{v}_i velocity of species i

\vec{N}_i molar flux of species i

The temperature and pressure are assumed to be constant. This implies that the number of moles of gas contained within the MLI panel must remain constant such that

$$\vec{N}_A + \vec{N}_B = 0 \quad (2)$$

where the subscript A refers to helium and the subscript B refers to nitrogen. Equation (2) implies that the molar flux of nitrogen gas out of the MLI panel must equal the molar flux of helium gas into the panel, and therefore $\vec{v}^* = 0$.

Because the diffusion coefficient is dependent primarily upon the temperature and pressure of the gases and is only slightly dependent upon the composition of the mixture, it can be assumed to be constant. The diffusion coefficient can be calculated by using the following equation (ref. 9):

$$D_{AB} = 1.1150 \times 10^{-5} \frac{\sqrt{T^3 \left(\frac{1}{M_A} + \frac{1}{M_B} \right)}}{P \sigma_{AB}^2 \Omega_{D,AB}} \quad (3)$$

where

D_{AB} diffusion coefficient, m^2/min

T temperature (294.4 K)

M_A molecular weight of helium (4.003)

M_B molecular weight of nitrogen (28.02)

P pressure (1 atm)

σ_{AB} Lennard-Jones parameter (3.129 Å), $(1/2)(\sigma_A + \sigma_B)$

$\Omega_{D,AB}$ dimensionless function of temperature and intermolecular potential field for 1 molecule of gas A and 1 molecule of gas B (0.7472)

With these values for gaseous helium and nitrogen at ambient temperature and pressure, the calculated diffusion coefficient is 4.115×10^{-3} square meter per minute (4.429×10^{-2} ft^2/min).

The binary diffusion equation (eq. (1)) can be simplified to the form

$$\frac{\partial C_A}{\partial t} = D_{AB} \nabla^2 C_A \quad (4)$$

by making use of the following assumptions:

- (1) Temperature and pressure are constant.
- (2) $\vec{v}^* = 0$
- (3) D_{AB} is constant.
- (4) No chemical reactions take place.

Equation (4) can be further simplified for a one-dimensional flow model in a rectangular coordinate system to

$$\frac{\partial C_A}{\partial t} = D_{AB} \frac{\partial^2 C_A}{\partial x^2} \quad (5)$$

where x is the distance from the no-flow boundary to the point at which the concentration is to be determined.

The solution for equation (5) is initially determined for a time-independent boundary condition at the edge of the MLI panel (i. e. , at time zero a step change from 100 percent gaseous nitrogen to 100 percent gaseous helium is assumed to take place at the edge of the panel). The initial and boundary conditions (fig. 29(b)) are

- (1) Initial condition at $t = 0$,

$$C_A = 0$$

- (2) Boundary condition at $x = L$,

$$C_A = C_{A0}$$

- (3) Boundary condition at $x = 0$,

$$\frac{\partial C_A}{\partial x} = 0$$

where L is the distance from the no-flow boundary to the edge of the panel and C_{A0} represents the molar concentration of pure helium for $t > 0$. The second boundary

condition assumes that there is no mass transfer across the centerline of the basic MLI panel because the concentration profile is symmetrical about the centerline.

Equation (5) is solved by applying separation of variables:

$$\frac{C_A}{C_{A0}} = 1 + \frac{2}{L} \sum_{n=0}^{\infty} \frac{(-1)^{n+1}}{\lambda_n} e^{-D_{AB}\lambda_n^2 t} \cos(\lambda_n x) \quad (6)$$

where

$$\lambda_n = \frac{(2n + 1)\pi}{2L}$$

Equation (6) then is the solution for the time-independent boundary condition of pure helium at the edge of the MLI panel.

Gaseous nitrogen concentration calculated as a function of distance from the centerline for a step change to 100 percent gaseous helium at the edge of the basic MLI panel at $t = 0$ is shown in figure 30. The analysis was based on equation (6) and a diffusion coefficient of 4.12×10^{-3} square meter per minute (4.43×10^{-2} ft²/min). These results indicate that the highest gradients in the purge gas concentrations occur at the edge of a panel, as might be expected. More importantly, these results also show that approximately 80 minutes were required to reduce the gaseous nitrogen concentration at the centerline of this panel to less than 1 percent. Any delay in reducing the nitrogen concentration at the edge of the panel to near zero results in a time-dependent boundary condition and will increase the required purge time.

Equation (6) can be written in dimensionless form to generalize the solution as follows:

$$C^* = 1 + 2 \sum_{n=0}^{\infty} \frac{(-1)^{n+1}}{\lambda_n^*} e^{-t^*(\lambda_n^*)^2} \cos(\lambda_n^* x^*) \quad (7)$$

where

$$C^* = \frac{C_A}{C_{A0}}$$

$$t^* = D_{AB} \frac{t}{L^2}$$

$$x^* = \frac{x}{L}$$

$$\lambda_n^* = (2n + 1) \frac{\pi}{2}$$

The solution for equation (7) is plotted as a function of x^* for a range of values of t^* in figure 31. The results show that the gaseous nitrogen concentration at the centerline of the panel can be reduced to 1 percent or less only when the value of t^* is approximately 2.0 or greater.

The solution of equation (6) for a time-dependent boundary condition was obtained by using Duhamel's superposition integral in the following form, as presented in reference 10:

$$\phi(x, t) = D(0)\psi(x, t) + \int_0^t \psi(x, t - s) \frac{dD(s)}{ds} ds \quad (8)$$

where

$\phi(x, t)$ solution for a time-dependent boundary condition

$D(0)$ equation of boundary condition at $t = 0$

$D(s)$ equation of boundary condition with s substituted for t

s substitution variable in Duhamel's superposition integral

and

$$\psi(x, t - s) = \frac{C_A}{C_{A0}} (x, t - s)$$

is the solution for the time-independent boundary condition with $(t - s)$ substituted for t .

Because the gaseous nitrogen concentration at the boundary ideally decreased to zero and would be expected to remain at that value, the most appropriate equation to fit the boundary condition was an exponential equation of the form

$$C_B = Ae^{bt} + Ce^{dt} + \dots \quad (9a)$$

or

$$C_A = 1 - (Ae^{bt} + Ce^{dt} + \dots) \quad (9b)$$

where $A, C \dots$ and $b, d \dots$ are constants. The equations used to curve fit the various experimentally determined boundary conditions for this investigation are presented in table II.

Equation (9b) was substituted into equation (8) and integrated, which resulted in the following equation for the solution of the gaseous nitrogen concentration at any point in the panel:

$$\begin{aligned} \varphi(x, t) = & (1 - A - C - \dots) \psi(x, t) + \left[A(1 - e^{bt}) + C(1 - e^{dt}) + \dots \right] \\ & + \left\{ \frac{2Ab}{L} \sum_{n=0}^{\infty} \frac{(-1)^{n+1}}{\lambda_n (D_{AB} \lambda_n^2 + b)} \left[e^{-D_{AB} \lambda_n^2 t} - e^{bt} \right] \cos (\lambda_n x) \right. \\ & \left. + \frac{2Cd}{L} \sum_{n=0}^{\infty} \frac{(-1)^{n+1}}{\lambda_n (D_{AB} \lambda_n^2 + d)} \left[e^{-D_{AB} \lambda_n^2 t} - e^{dt} \right] \cos (\lambda_n x) + \dots \right\} \end{aligned} \quad (10)$$

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TABLE I. - SUMMARY OF CONDITIONS FOR AND RESULTS OF GASEOUS HELIUM PURGE TESTS OF MULTILAYER INSULATION

Test	Type of multilayer insulation (MLI) panel	Orientation	Time at which purge rate was reduced, min	Gaseous helium purge rates			At boundary	Within panel	Total volume of gaseous helium required to reach 1 percent gaseous nitrogen concentration within panel, std m ³
				MLI panel volumes per hour	Purge-box volumes per hour	Total, std m ³ /hr			
1A	Basic	Horizontal	---	20.5 4.8	19.4 3.3	1.51 .28	77	115	2.59
1B	Basic		100	20.5	19.4	1.51	101	132	2.03
1C	Basic		69	4.8	3.3	.28	92	134	2.02
2A	With butt joint		---	20.6 4.8	19.5 3.3	1.51 .28	207	a280	1.73
2B			---	5.2	4.8	.38	157	214	2.75
2C			---	9.4	10.2	.77	157	214	2.75
2D			---	9.5	10.2	.77	124	185	4.90
2E			---	20.0	20.9	1.59	124	188	1.88
2F			---	19.9	4.8	.60	124	200	1.00
2G			---	20.2	0	.30	108	174	1.31
2H			---	30.6		.45	82	152	1.52
2I			---	40.6		.60	196	245	.57
2J			---	9.5		.14	196	245	.57
2K		Vertical	---				145	b226	.53
2L	With butt joint and uncovered grommets	Horizontal	---				191	247	.58

^aExtrapolated value.^bExtrapolated value for bottom of MLI panel.

TABLE II. - EQUATIONS OF BOUNDARY CONDITIONS
FOR EXPERIMENTAL TESTS

Test	Equation
1A to 1C	$\%GN_2 = (0.0321 e^{-0.0127t} + 0.2364 e^{-0.0614t} + 0.7315 e^{-0.2250t}) \times 100$
2D to 2F	$\%GN_2 = (0.0334 e^{-0.0109t} + 0.2459 e^{-0.0404t} + 0.7207 e^{-0.1768t}) \times 100$
2F	$\%GN_2 = (0.0565 e^{-0.0138t} + 0.1789 e^{-0.0369t} + 0.6123 e^{-0.1310t}) \times 100$
2G	$\%GN_2 = (0.0419 e^{-0.0138t} + 0.2068 e^{-0.0534t} + 0.1409 e^{-0.2101t}) \times 100$
2H	$\%GN_2 = (0.0554 e^{-0.0209t} + 0.2816 e^{-0.0782t} - 0.0799 e^{-0.0733t}) \times 100$
2I to 2J	$\%GN_2 = (0.1511 e^{-0.0145t} + 0.6557 e^{-0.0330t} + 0.1932 e^{-0.0395t}) \times 100$

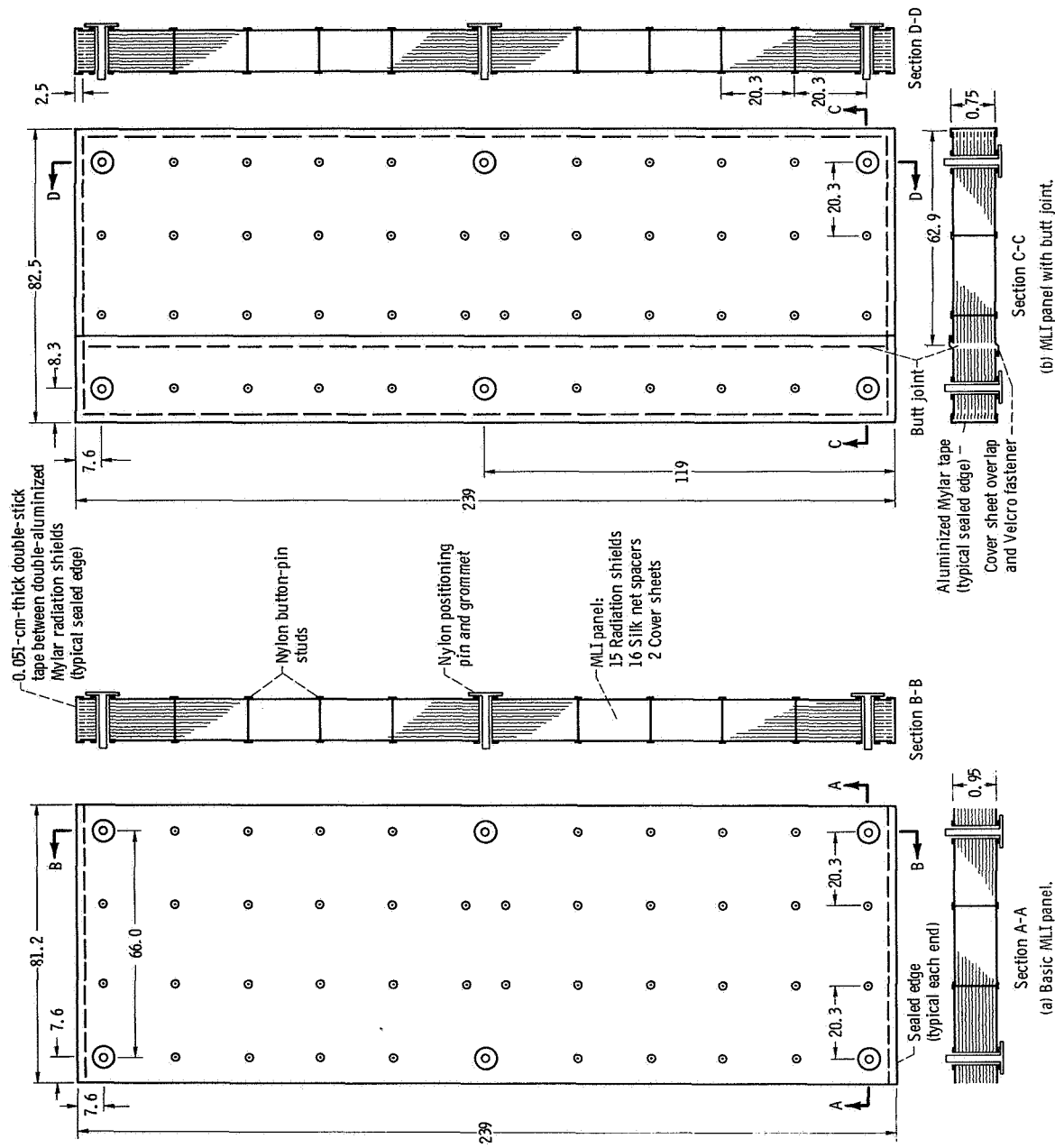


Figure 1. - Multilayer insulation (MLI) panels. (All dimensions are in cm.)

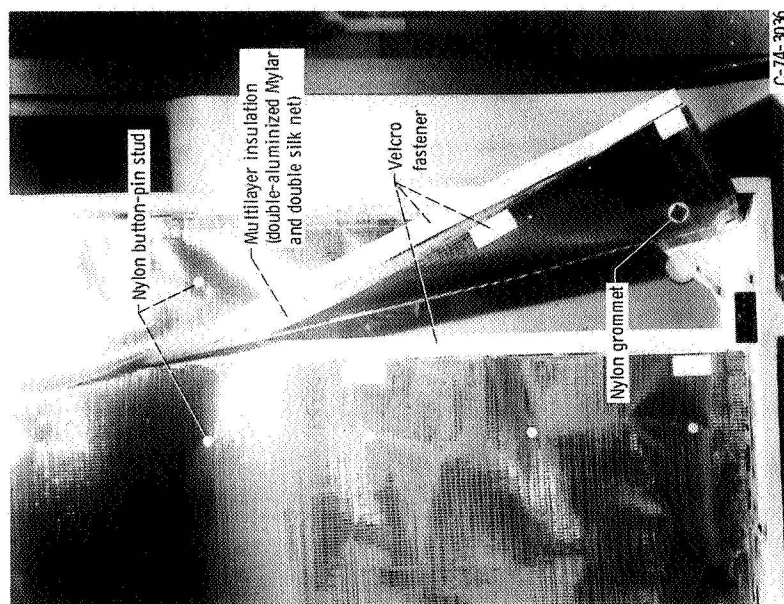


Figure 2. - Butt joint configuration.

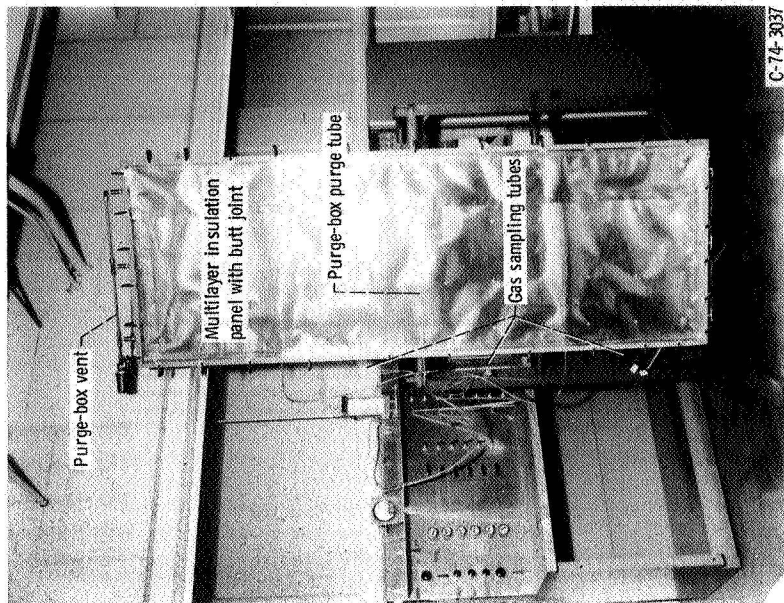


Figure 3. - Purge box.

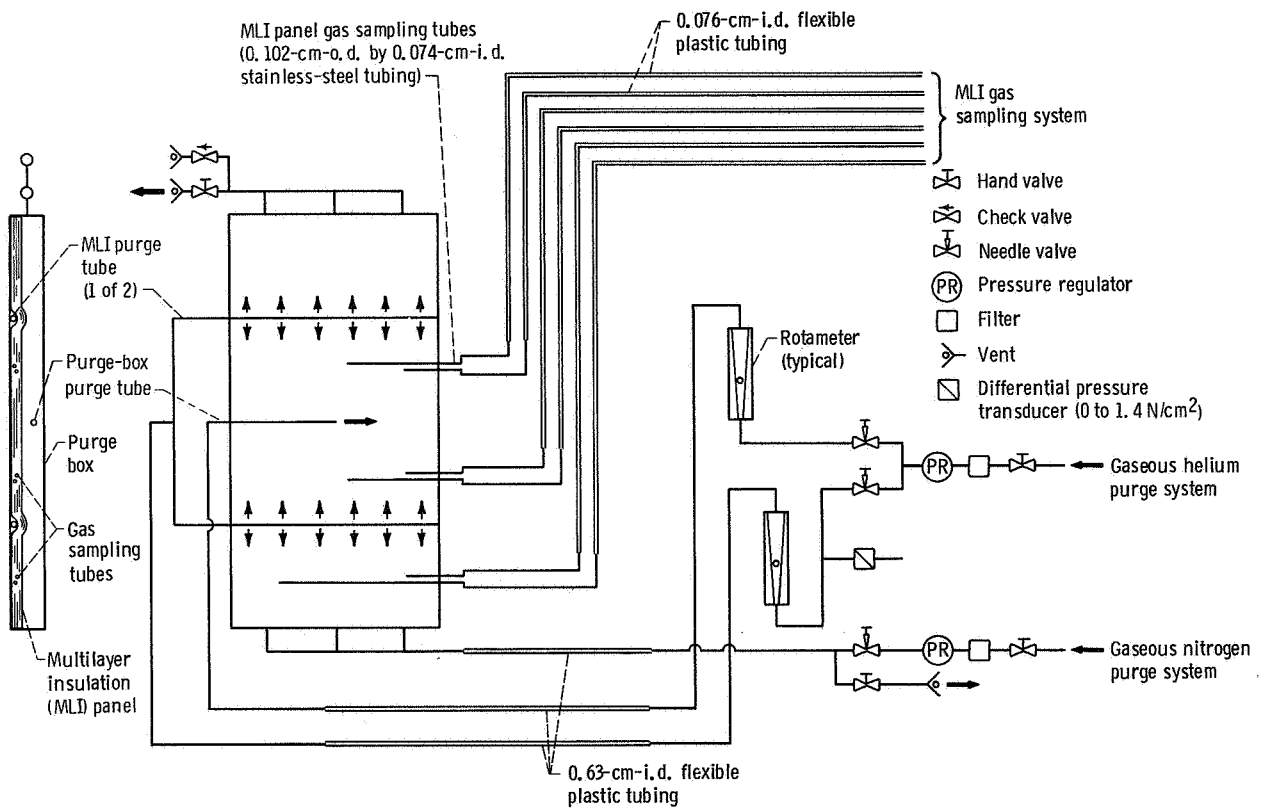


Figure 4. - Flow schematic of purge and gas sampling systems.

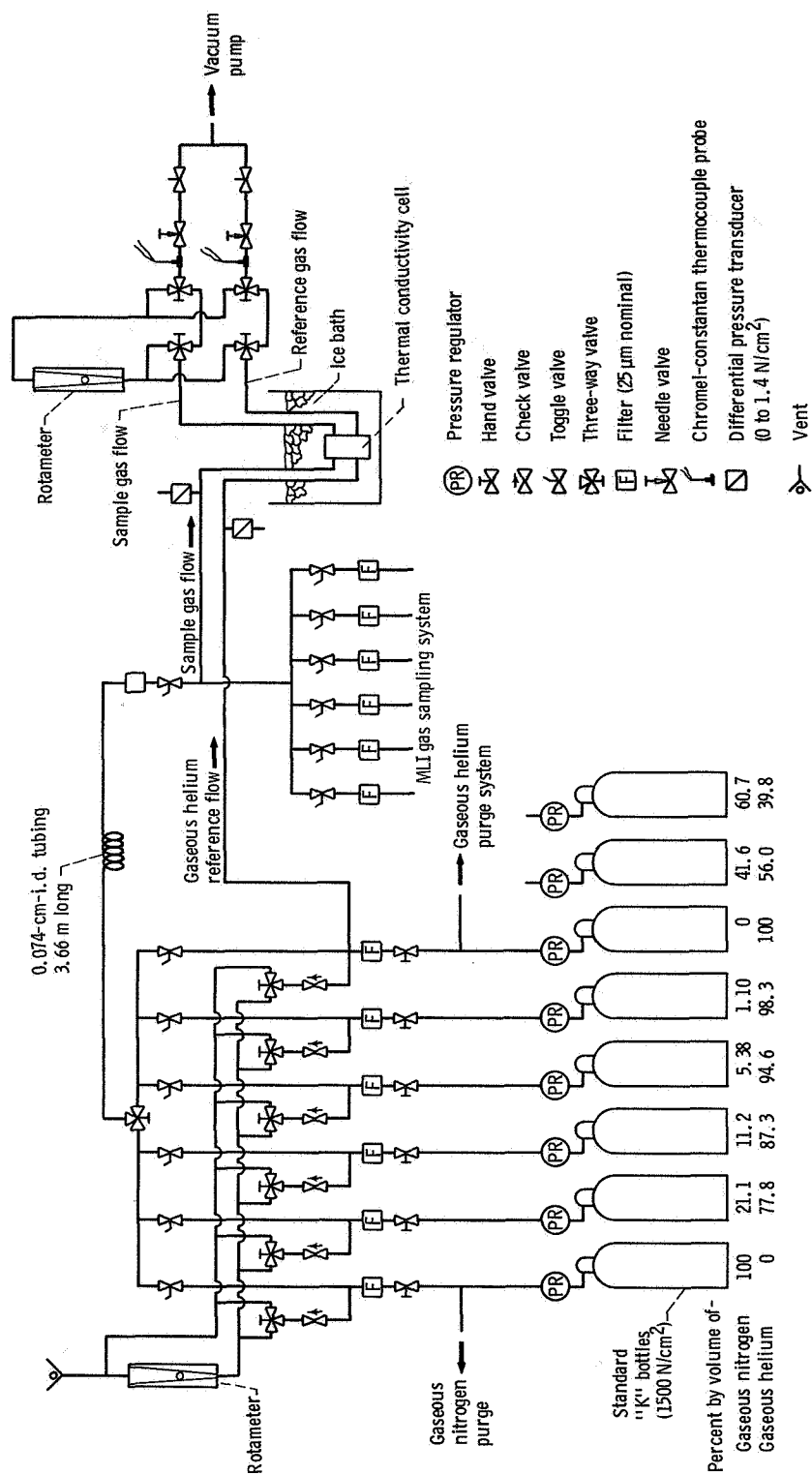


Figure 5. - Flow schematic of gas concentration measurement system.

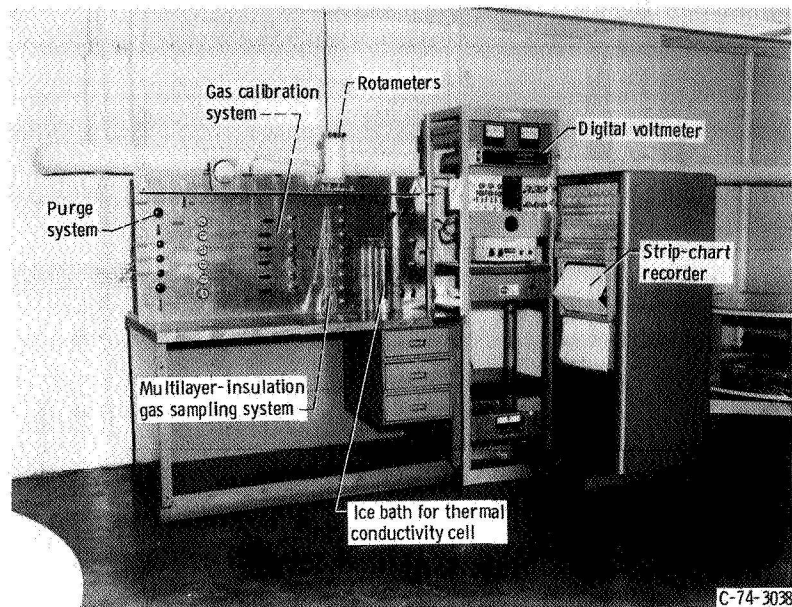


Figure 6. - Flow-control panel for gas concentration measurement.

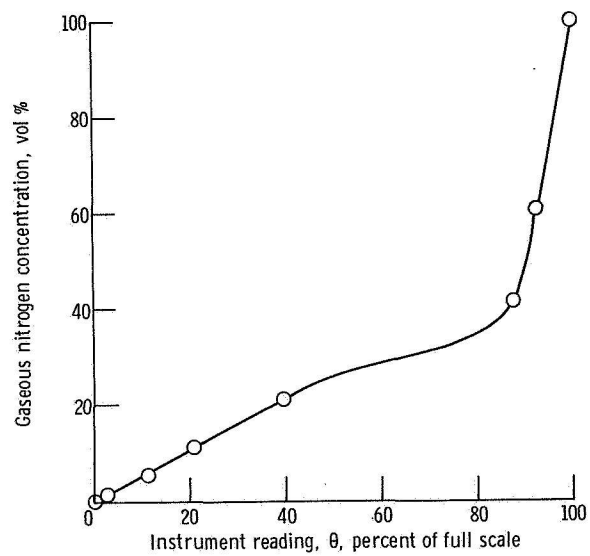


Figure 7. - Calibration curve for thermal conductivity cell, with gaseous helium reference.

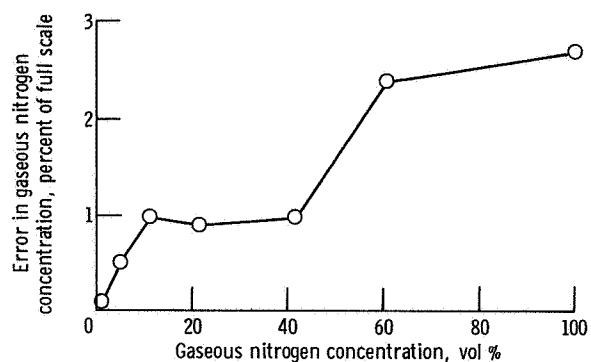


Figure 8. - Maximum error in determining gaseous nitrogen concentration due to instrumentation drift during steady-state calibration.

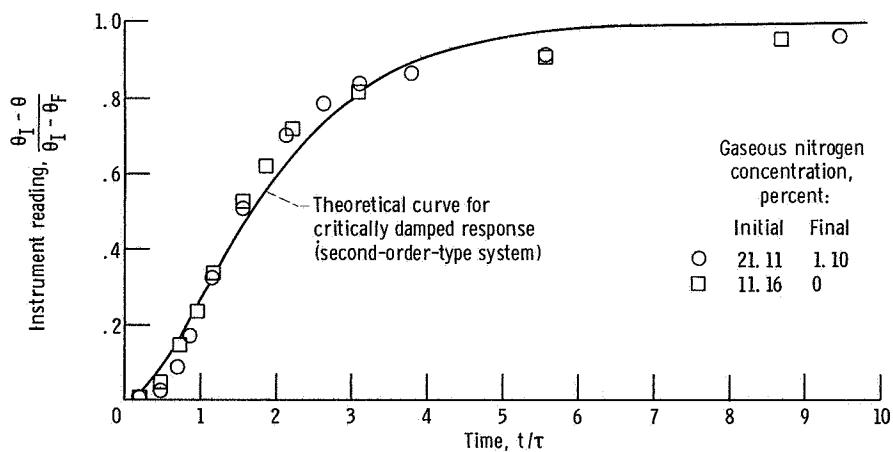


Figure 9. - Comparison of responses of a thermal conductivity cell and a second-order-type system to a step change. Assumed time constant, 0.0855 minute.

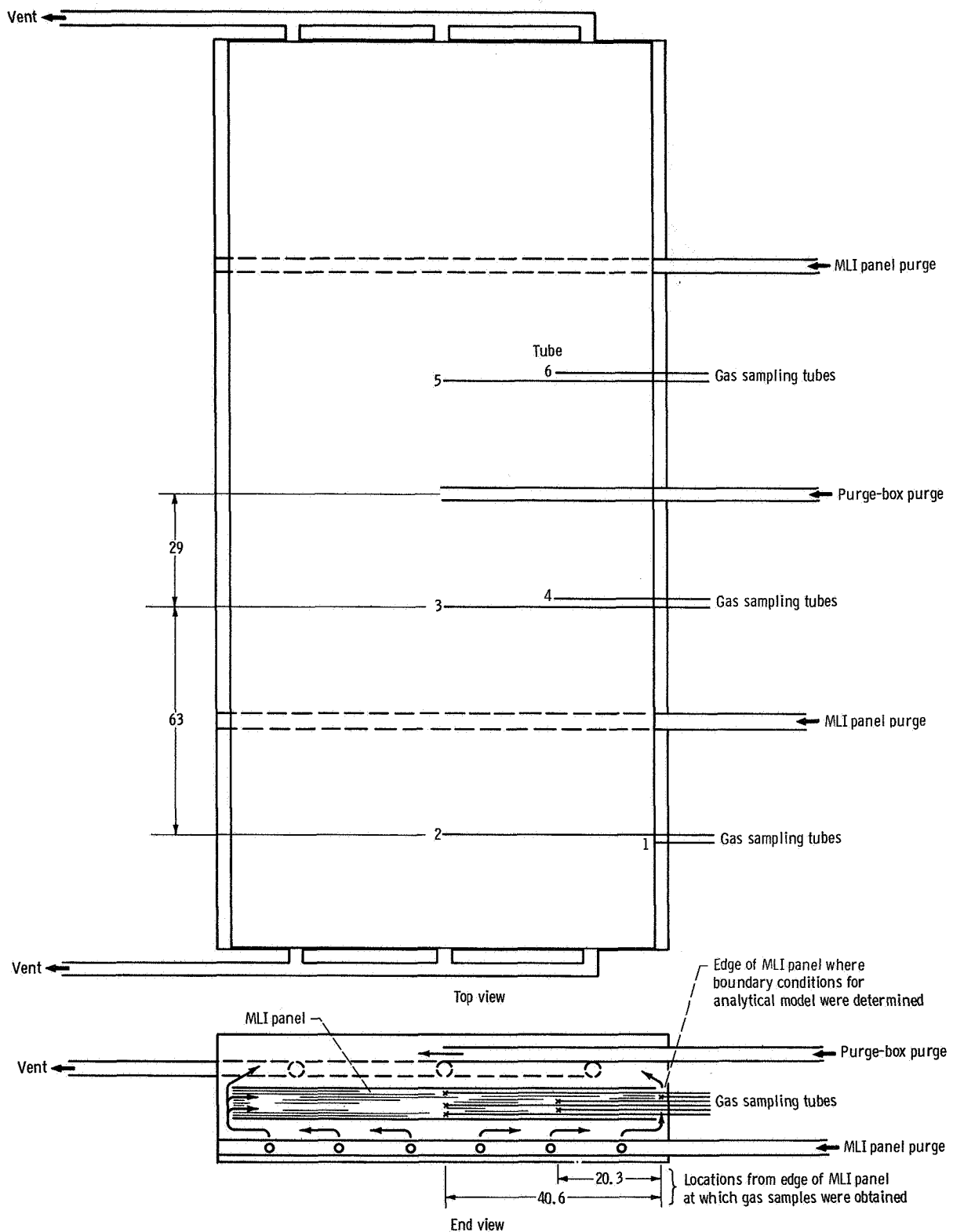


Figure 10. - Schematic of gaseous helium purge flow path and gas sampling locations for basic multilayer insulation (MLI) panel. (All dimensions are in cm.)

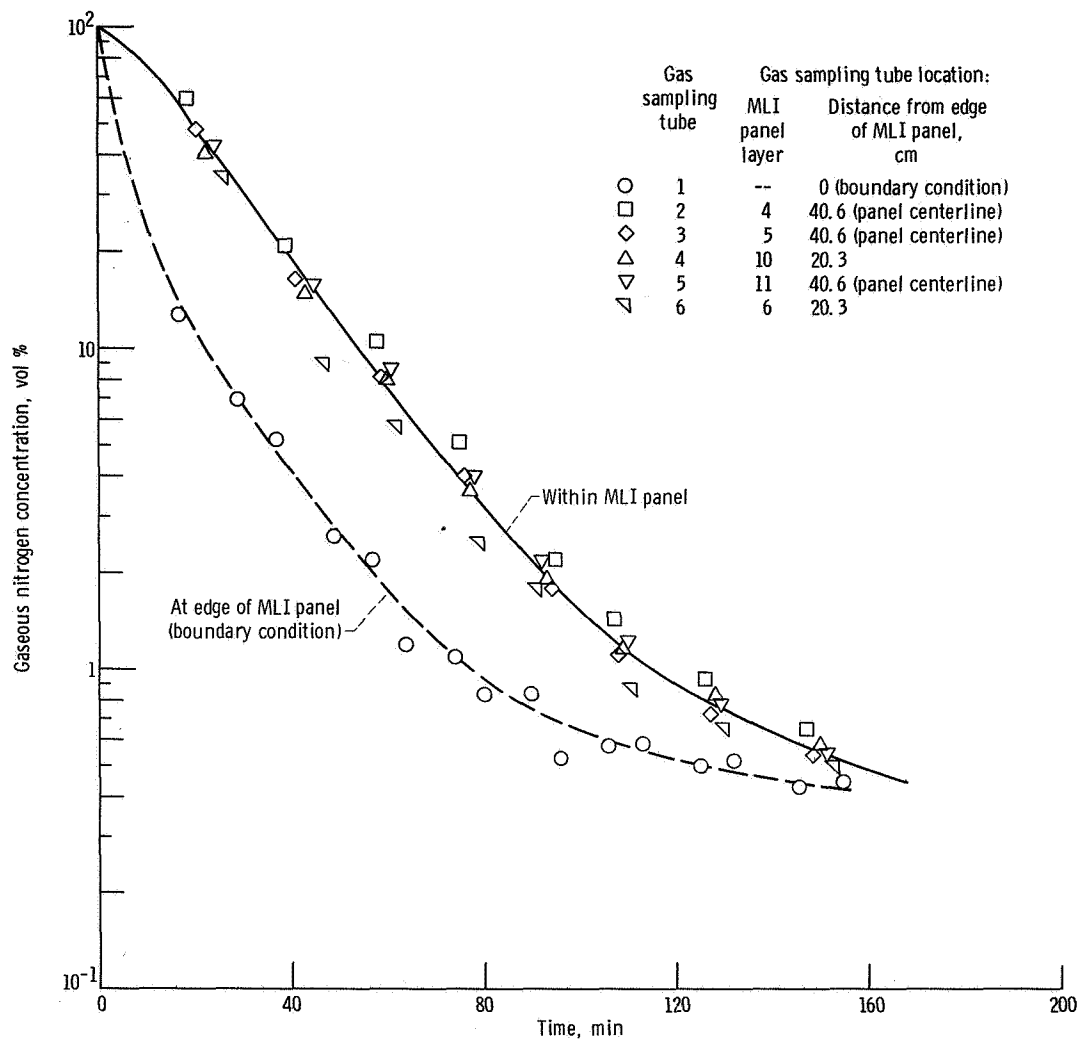


Figure 11. - Experimentally determined gaseous nitrogen concentrations for basic multilayer insulation (MLI) panel. Test 1A; horizontal orientation; initial gaseous helium purge rate, 20 volumes per hour.

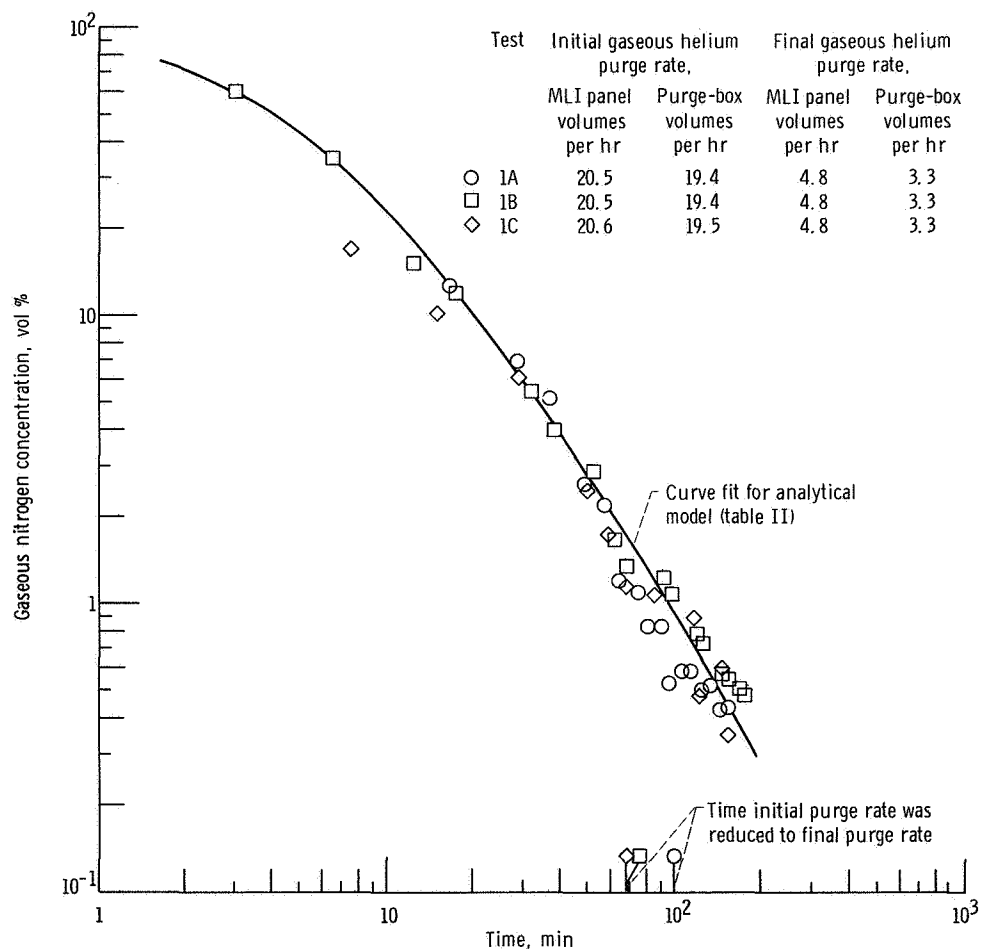


Figure 12. - Gaseous nitrogen concentration at edge of multilayer insulation (MLI) panel (boundary condition). Tests 1A to 1C; horizontal orientation; all data for gas sampling tube 1.

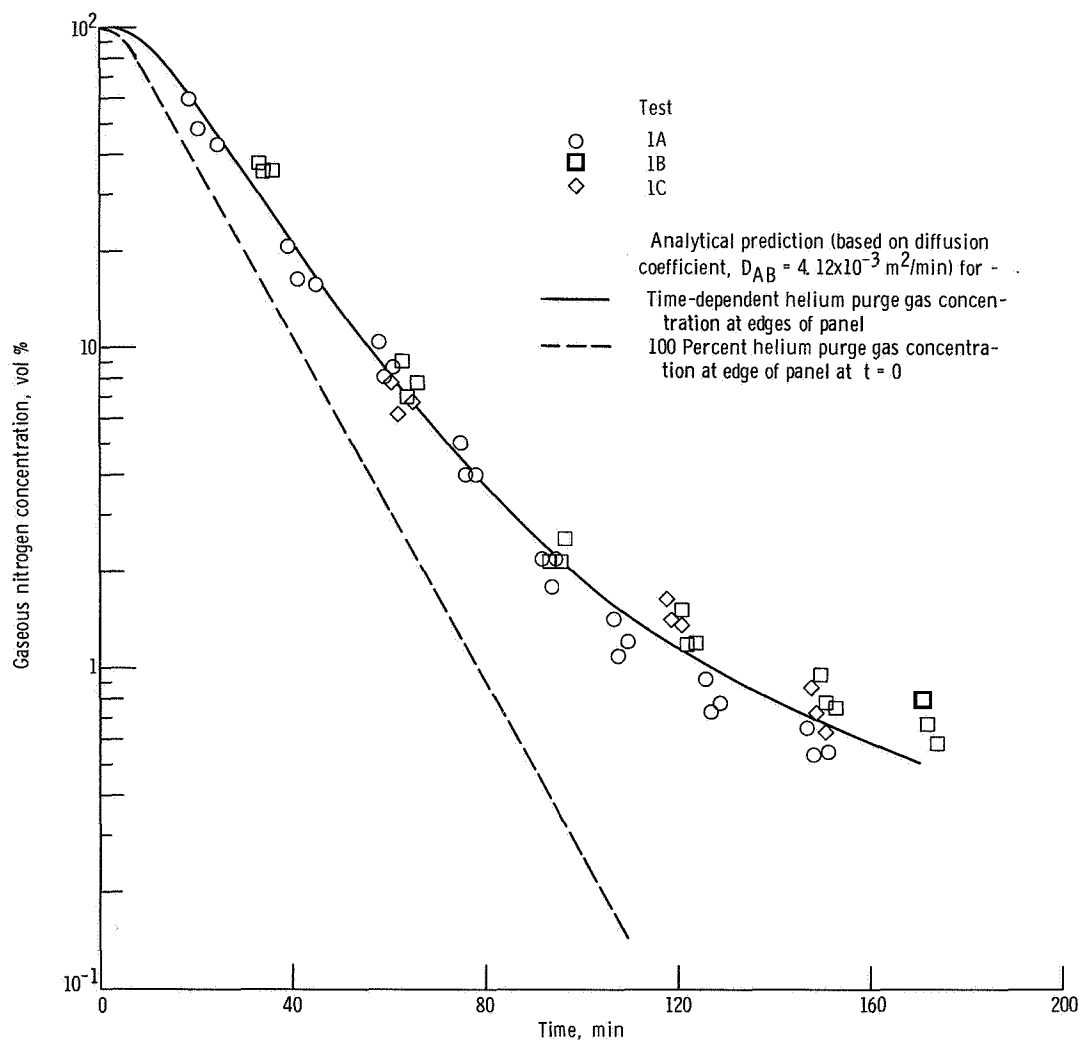


Figure 13. - Comparison of analytically and experimentally determined gaseous nitrogen concentrations at centerline of basic multilayer insulation (MLI) panel. Tests 1A to 1C; horizontal orientation.

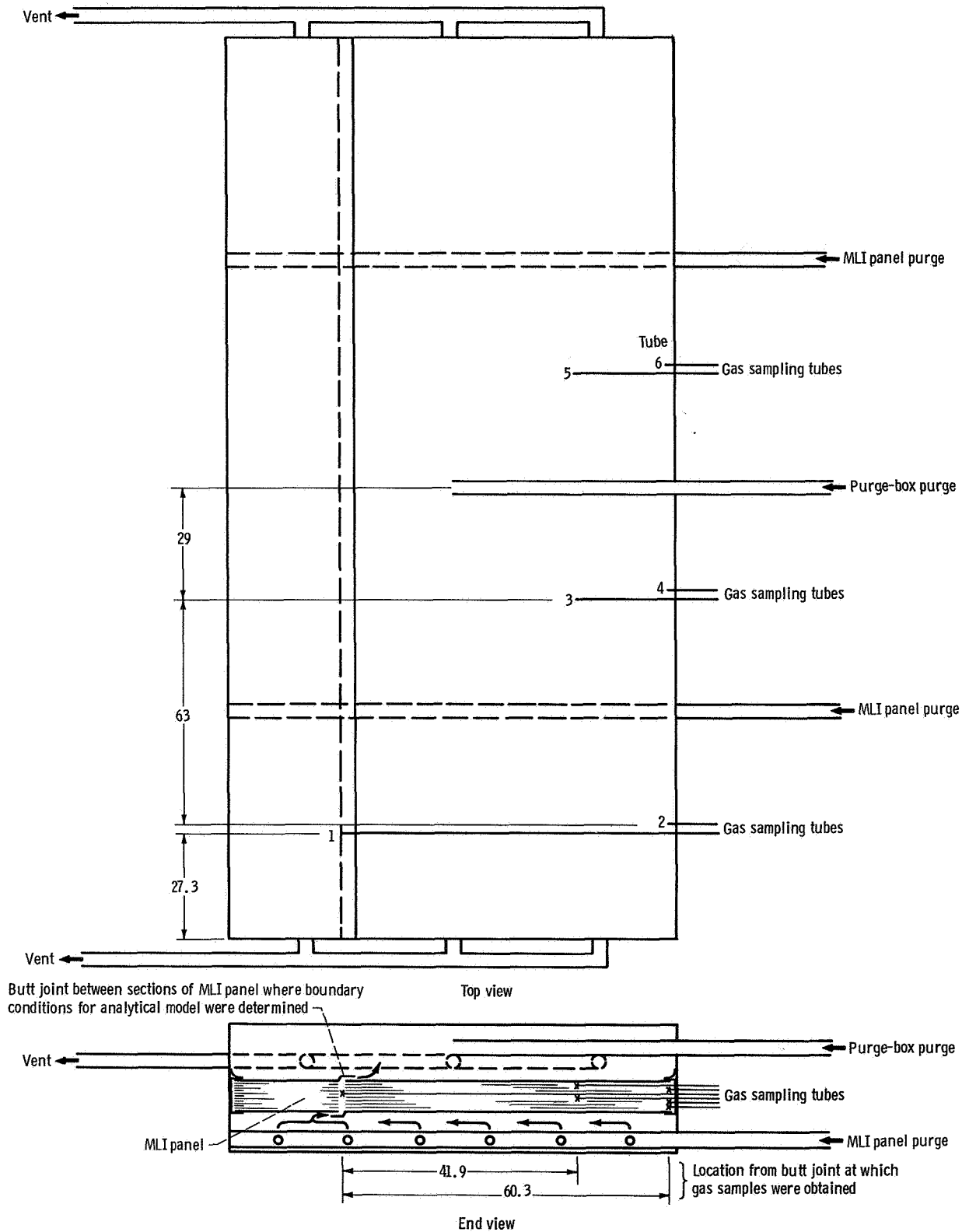


Figure 14. - Schematic of gaseous helium purge flow path and gas sampling locations for multilayer insulation (MLI) panel with butt joint. (All dimensions are in cm.)

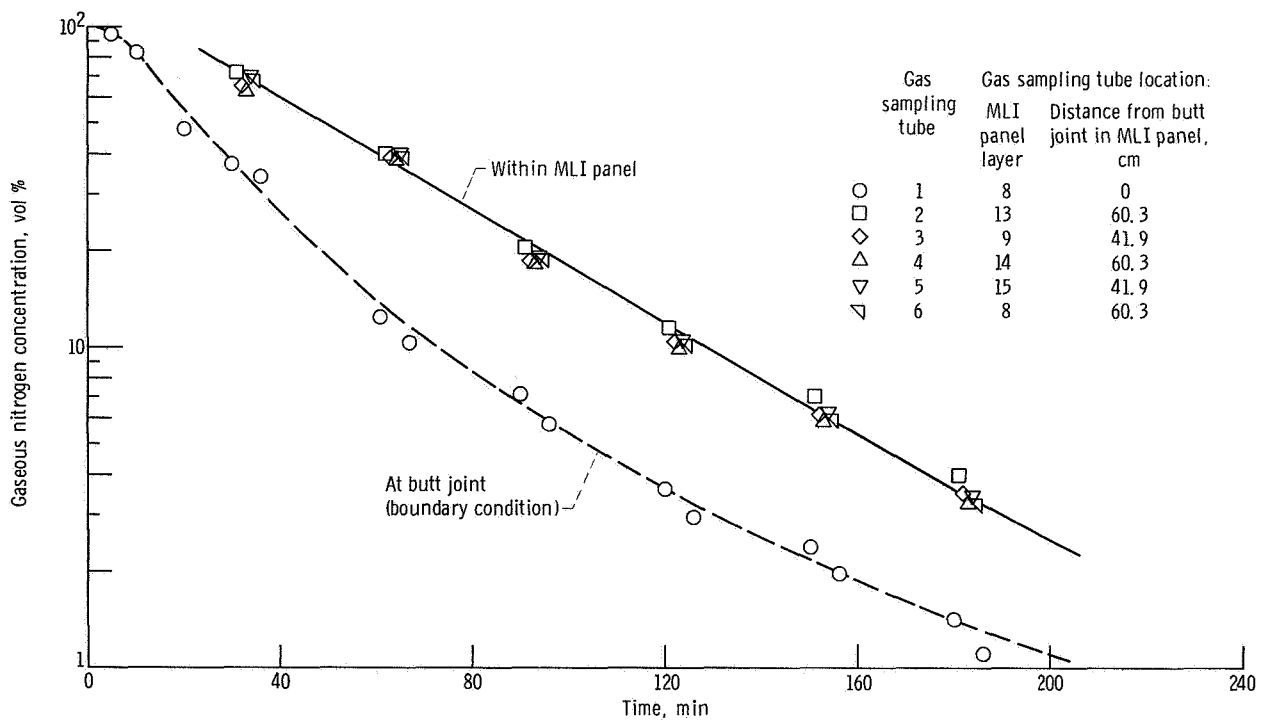


Figure 15. - Experimentally determined gaseous nitrogen concentration for multilayer insulation (MLI) panel with butt joint. Test 2A; horizontal orientation; gaseous helium purge rate, 5 volumes per hour.

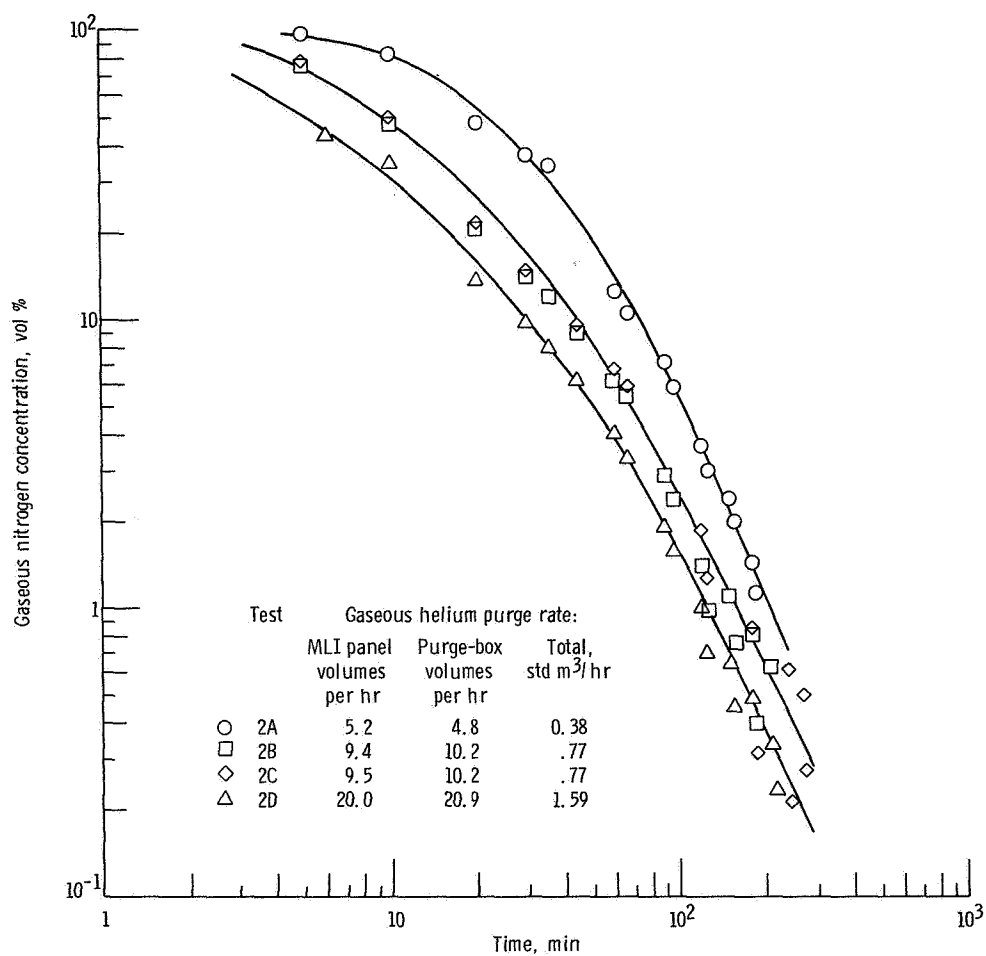


Figure 16. - Effect of change in total gaseous helium purge rate on the boundary conditions for multilayer insulation (MLI) panel with butt joint. Tests 2A to 2D; horizontal orientation; all data for gas sampling tube 1.

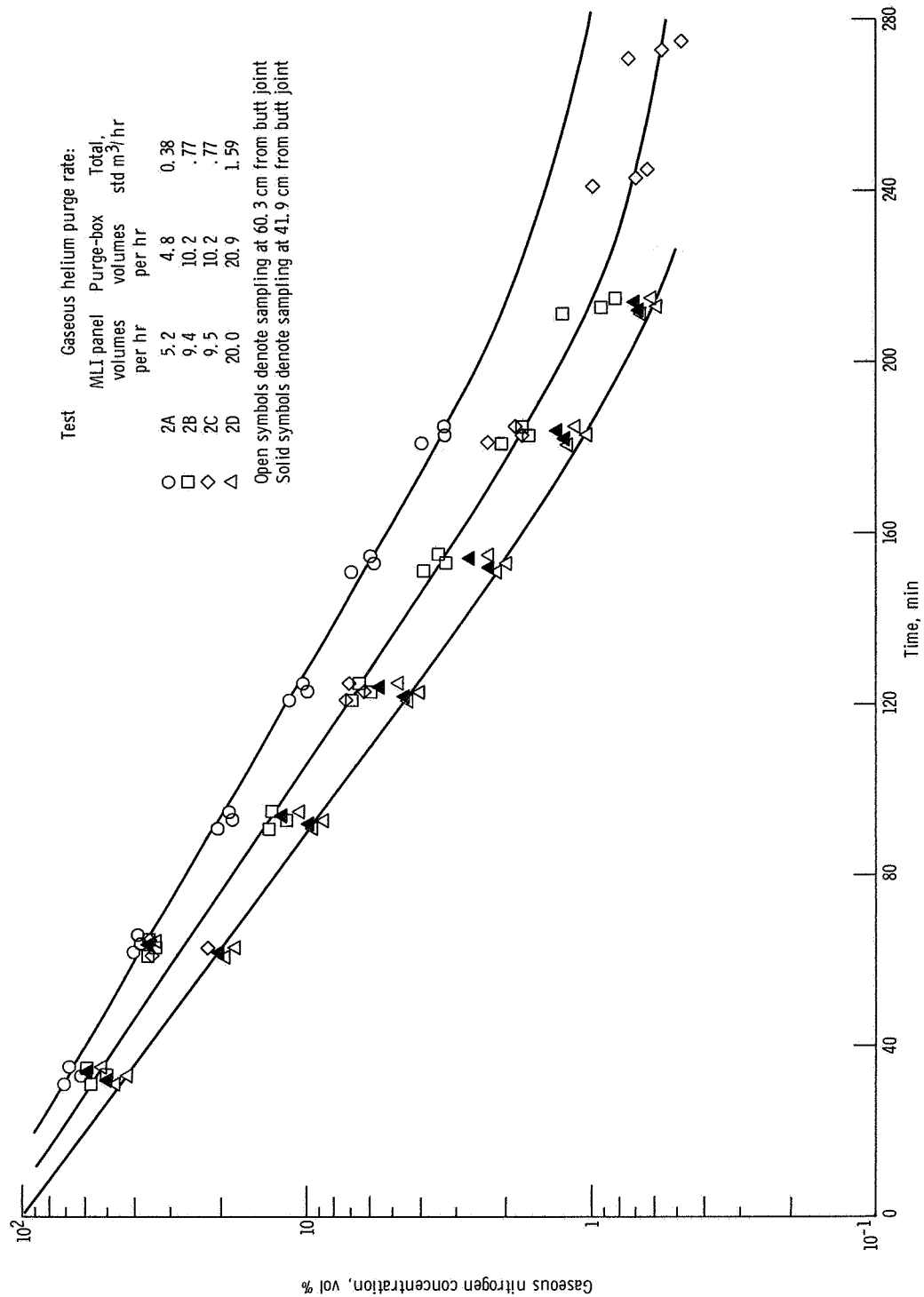


Figure 17. - Effect of change in total gaseous helium purge rate on gaseous nitrogen concentration within multilayer insulation (MLI) panel with butt joint. Tests 2A to 2D; horizontal orientation.

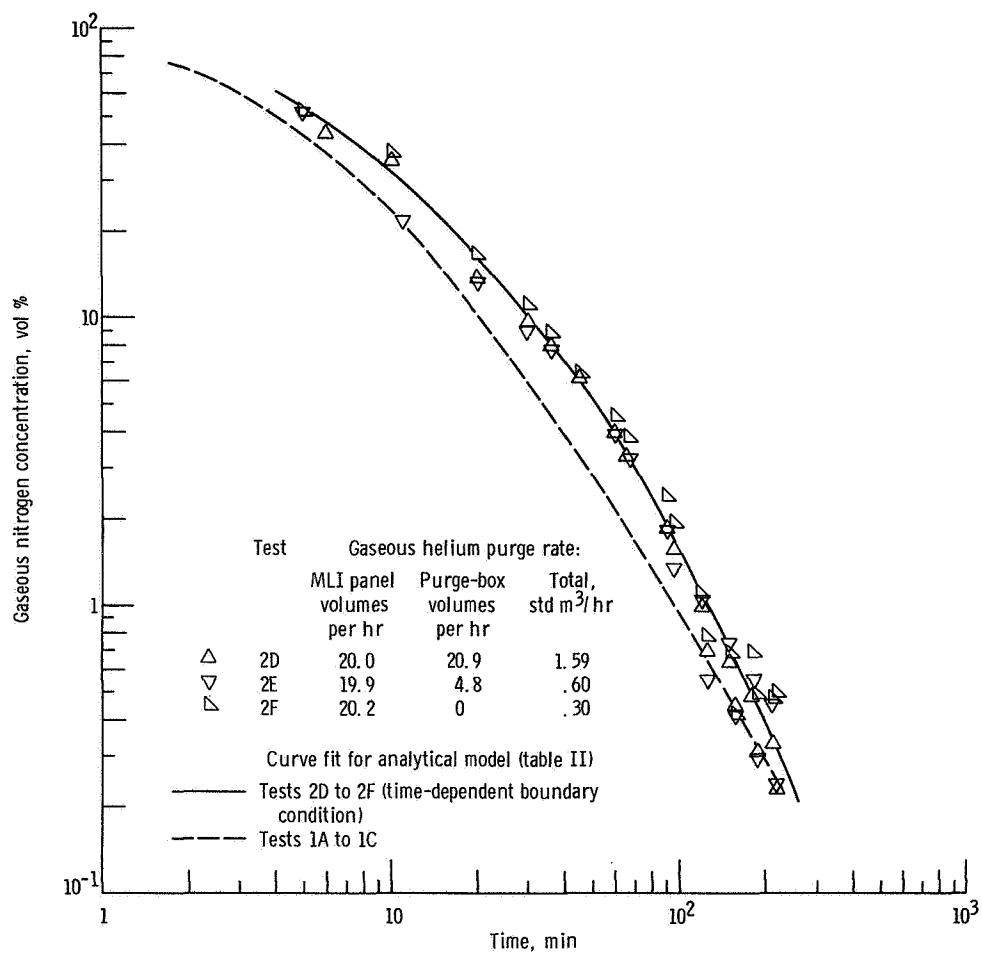


Figure 18. - Effect of change in purge-box gaseous helium purge rate on boundary conditions for multilayer insulation (MLI) panel with butt joint. Tests 2D to 2F; horizontal orientation; all data for gas sampling tube 1.

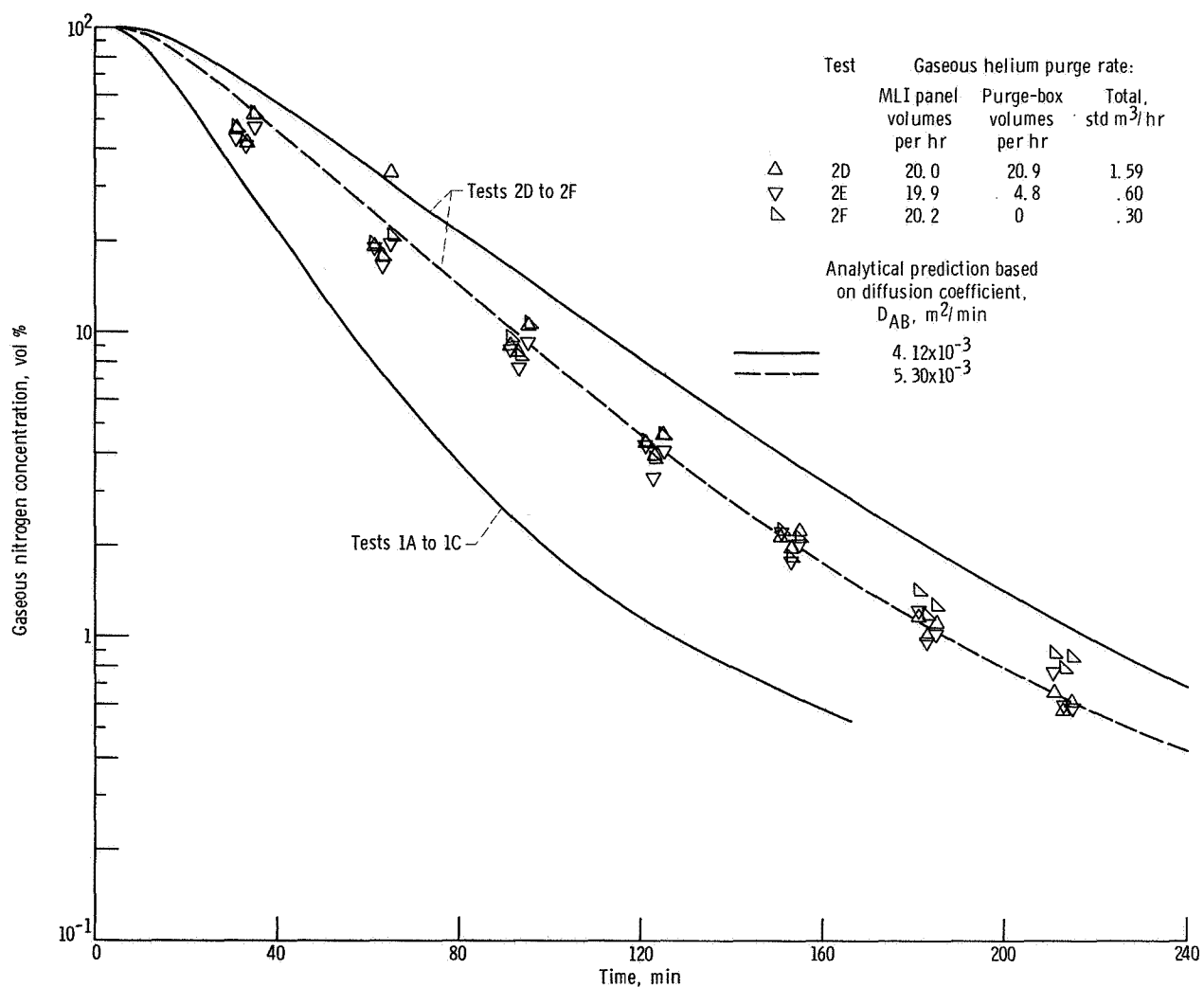


Figure 19. - Effect of change in purge-box gaseous helium purge rate on gaseous nitrogen concentration 60.3 centimeters from butt joint within multilayer insulation (MLI) panel. Tests 2D to 2F; horizontal orientation.

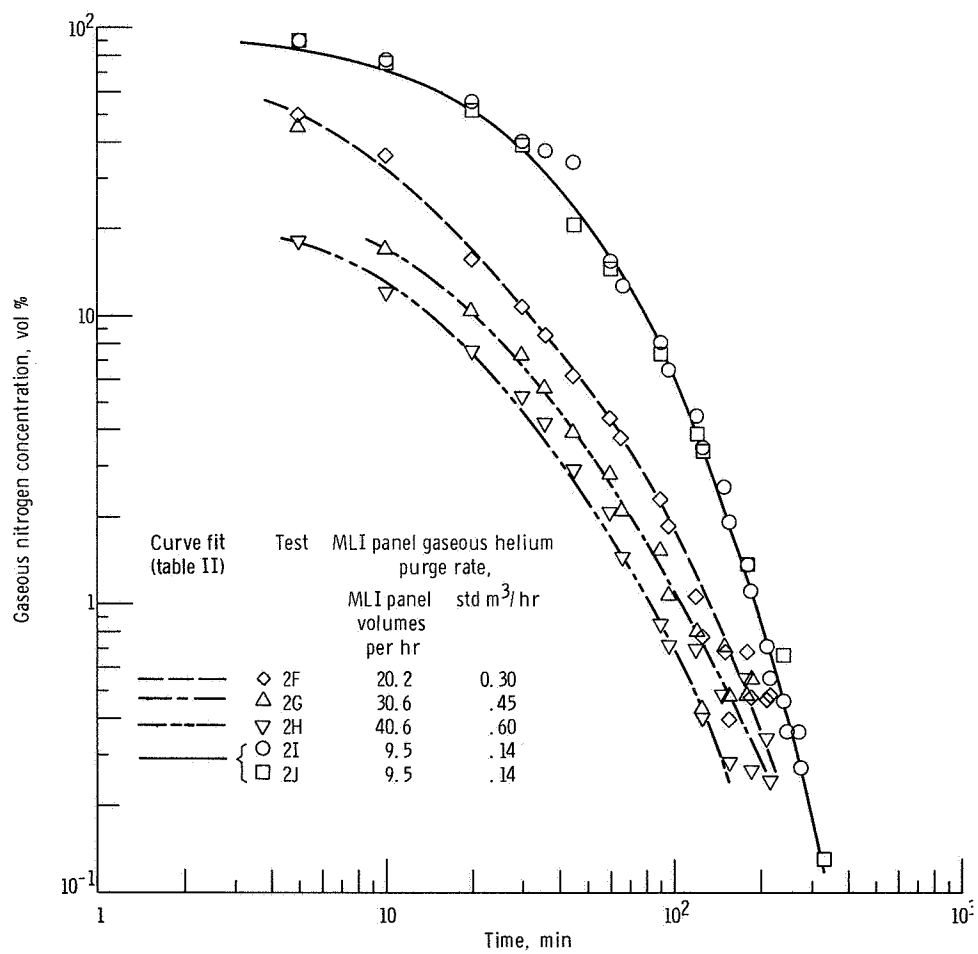


Figure 20. - Effect of change in multilayer insulation (MLI) panel gaseous helium purge rate on boundary conditions for MLI panel with butt joint. Tests 2F to 2J; horizontal orientation; all data for gas sampling tube 1.

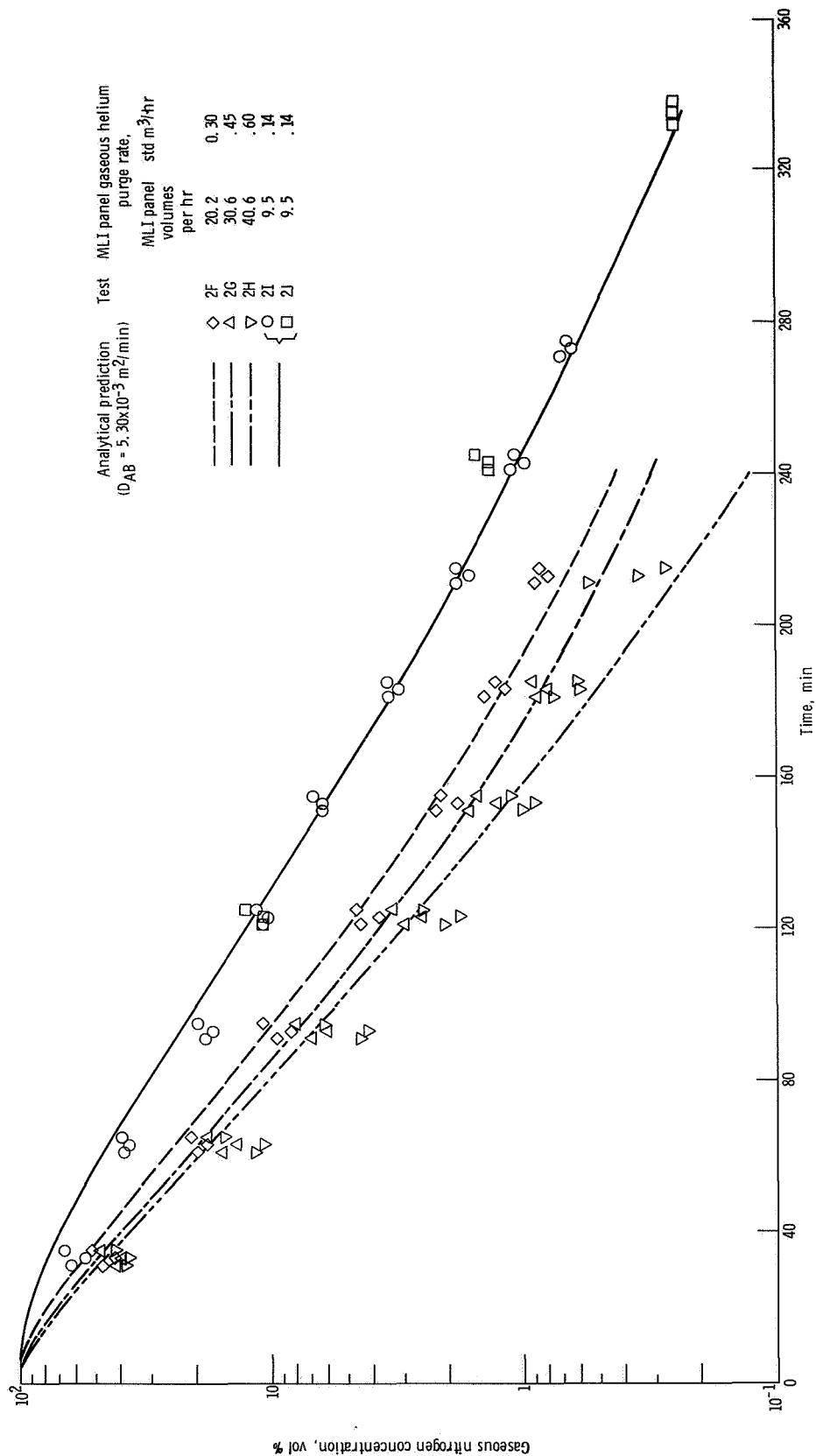


Figure 21. - Effect of change in multilayer insulation (MLI) panel gaseous helium purge rate on gaseous nitrogen concentration 60.3 centimeters from butt joint with in MLI panel. Tests 2F to 2J; horizontal orientation.

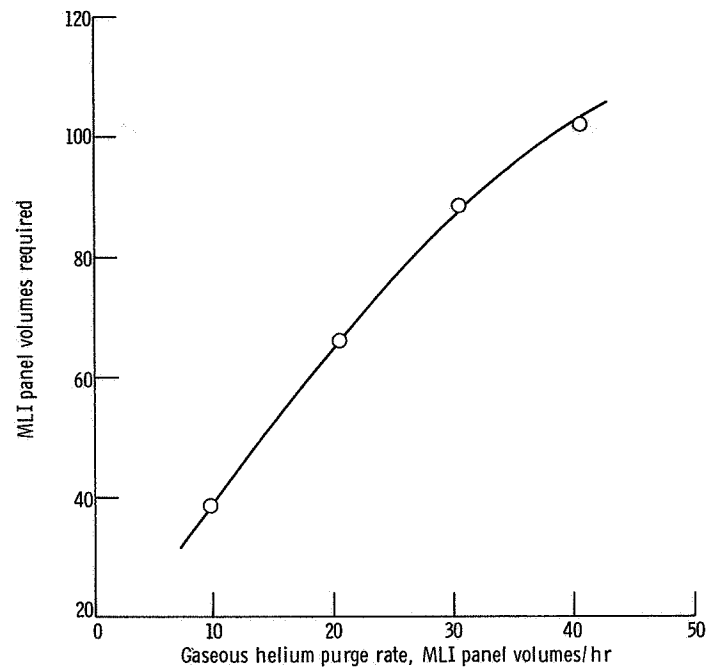


Figure 22. - Amount of gaseous helium purge gas required to achieve gaseous nitrogen concentration of 1 percent within multilayer insulation (MLI) panel with butt joint. Tests 2F to 2J.

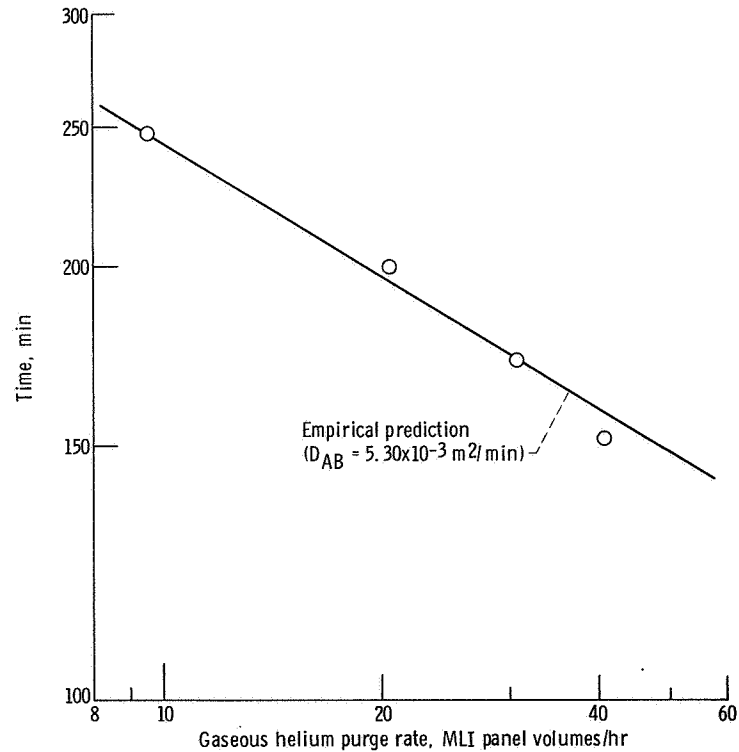


Figure 23. - Time required to achieve gaseous nitrogen concentration of 1 percent within multilayer insulation (MLI) panel with butt joint. Tests 2F to 2J.

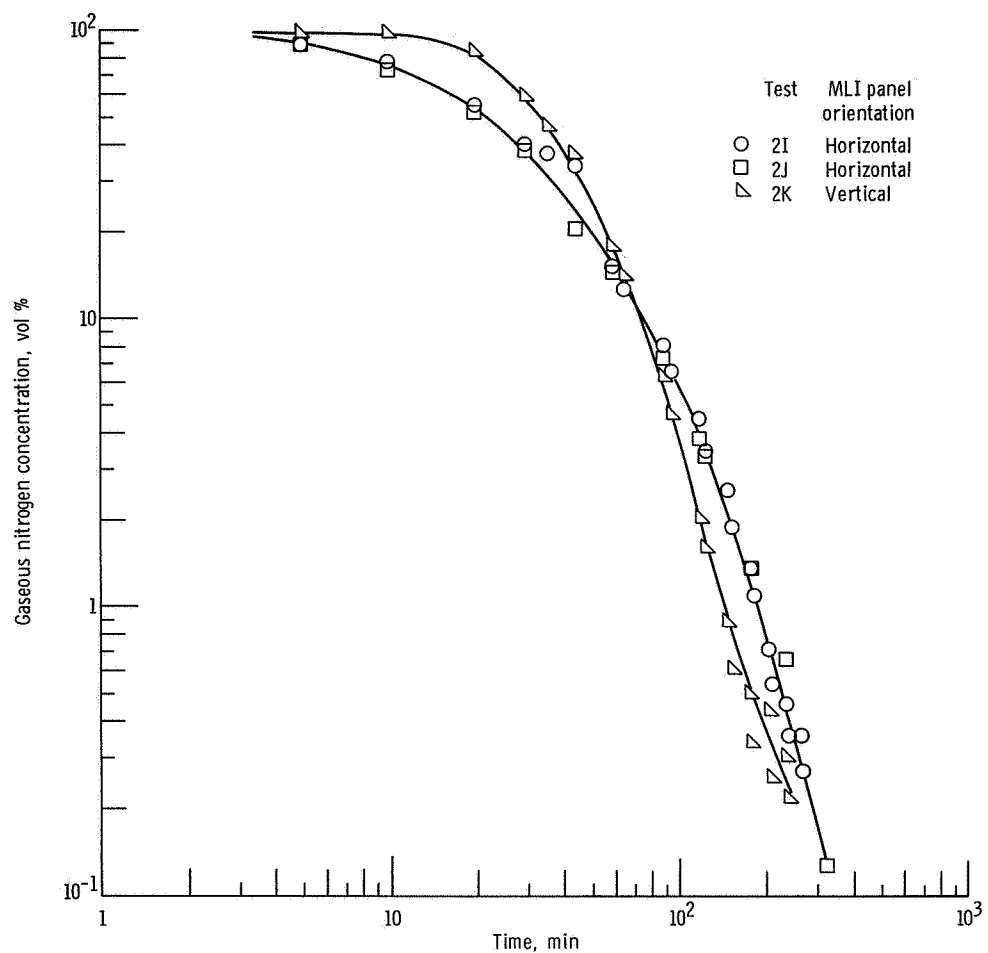


Figure 24. - Effect of vertical orientation on boundary conditions for multilayer insulation (MLI) panel with butt joint. Tests 2I to 2K; MLI panel gaseous helium purge rate, 9.5 MLI panel volumes per hour (0.14 std m³/hr); all data for gas sampling tube 1.

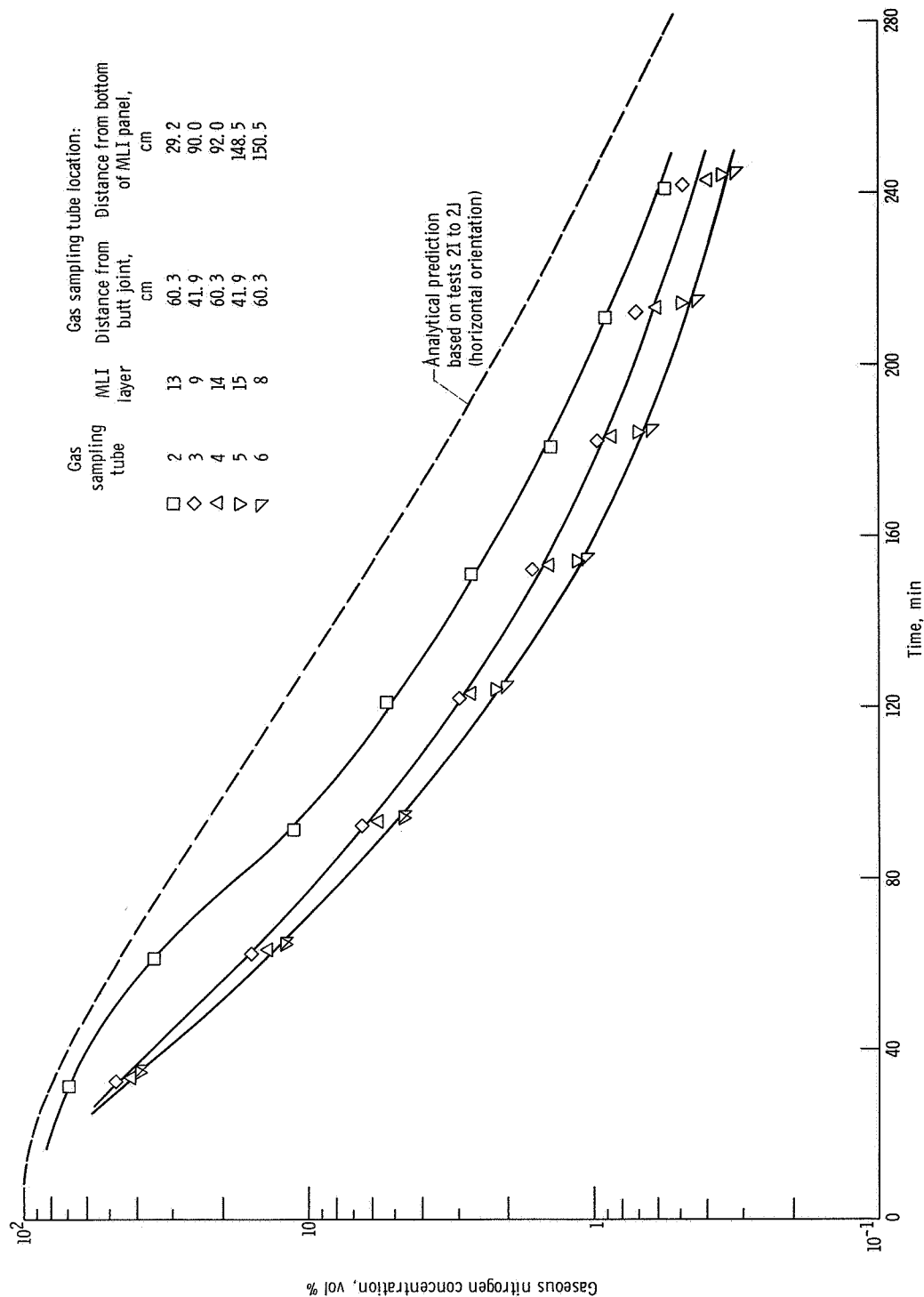


Figure 25. - Effect of vertical orientation on gaseous nitrogen concentration with in multilayer insulation (MLI) panel with butt joint. Test 2K.

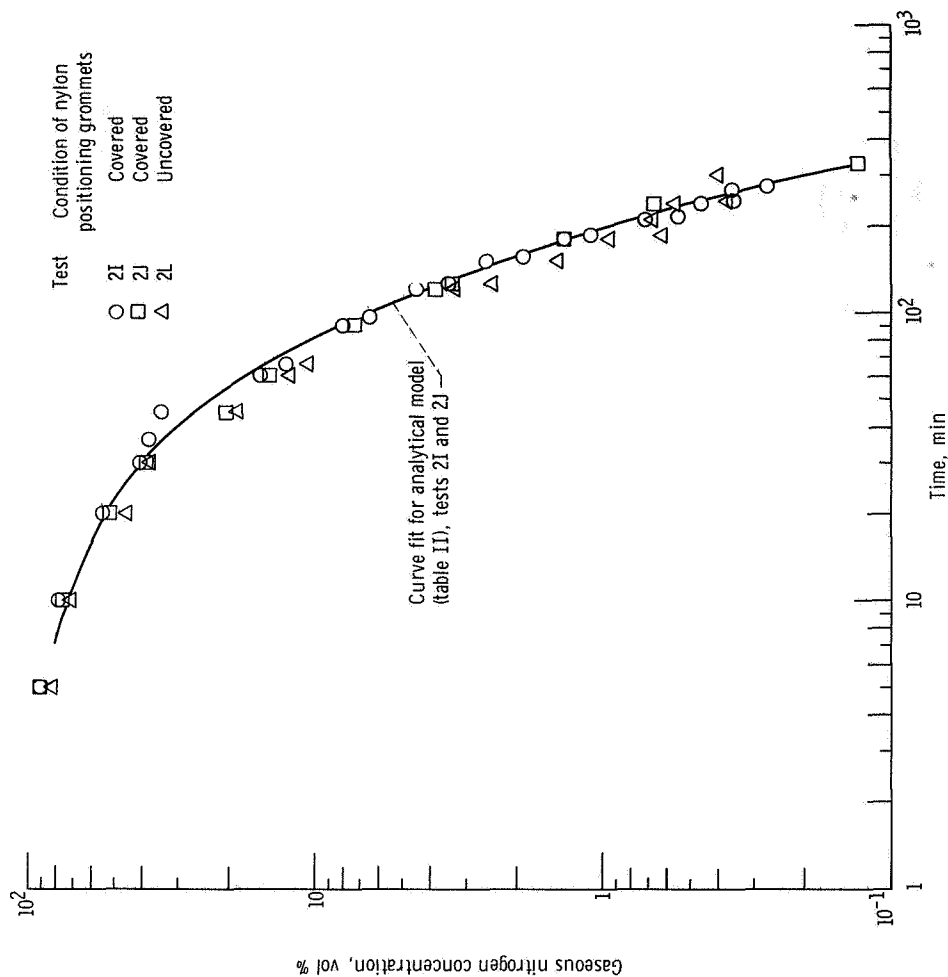


Figure 27. - Effect of uncovering grommets on boundary conditions for multilayer insulation (MLI) panel with butt joint. Tests 2I, 2J, and 2L; horizontal orientation; MLI panel gaseous helium purge rate, 9.5 MLI panel volumes per hour (0.14 std m³/hr); all data for gas sampling tube 1.

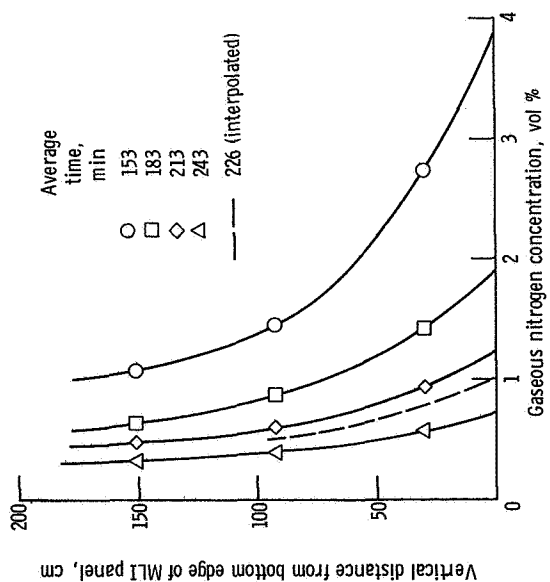


Figure 26. - Estimated time required to reach gaseous nitrogen concentration of 1 percent at bottom of multilayer insulation (MLI) panel 60.3 centimeters from butt joint. Test 2K; vertical orientation.

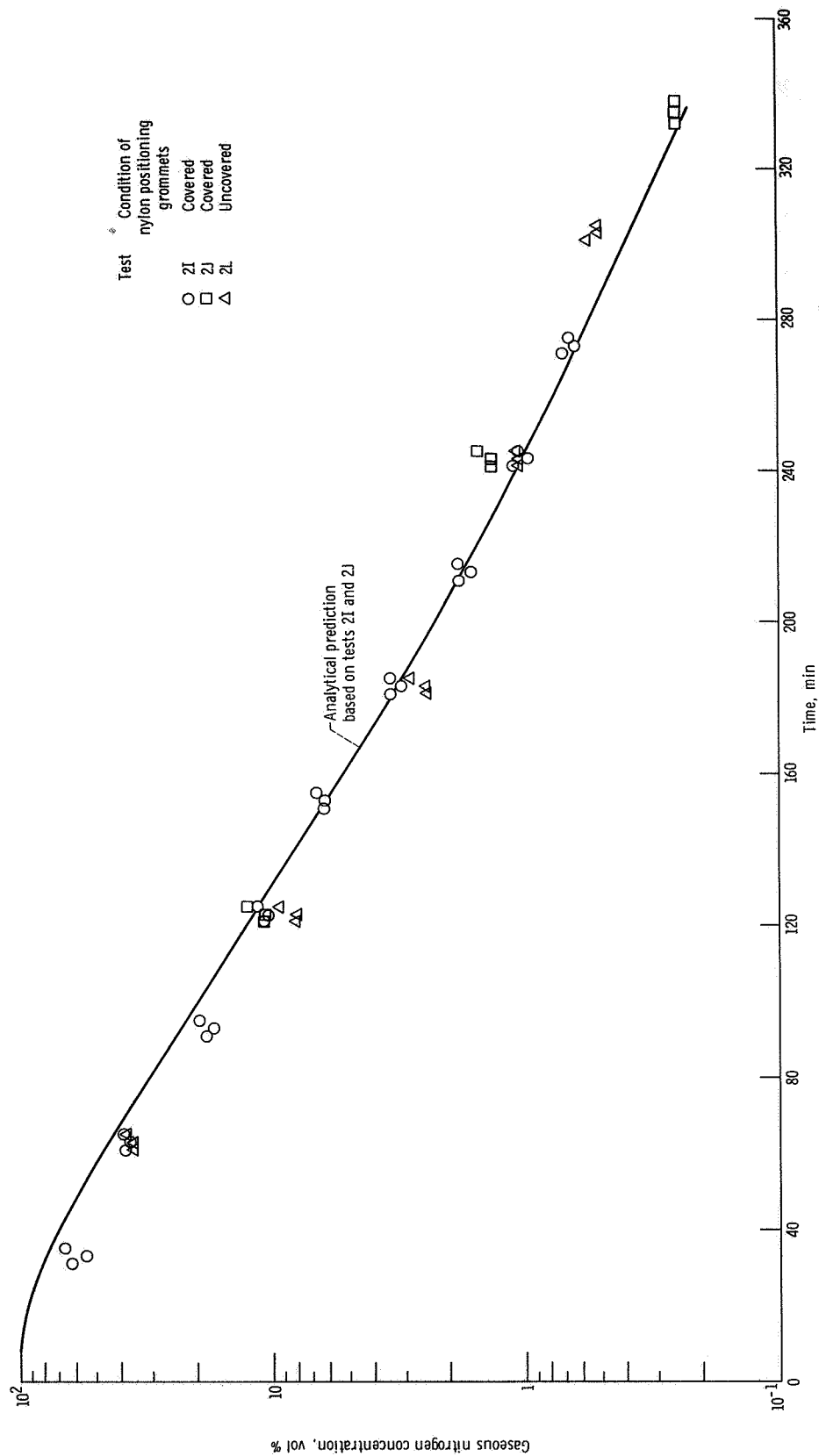
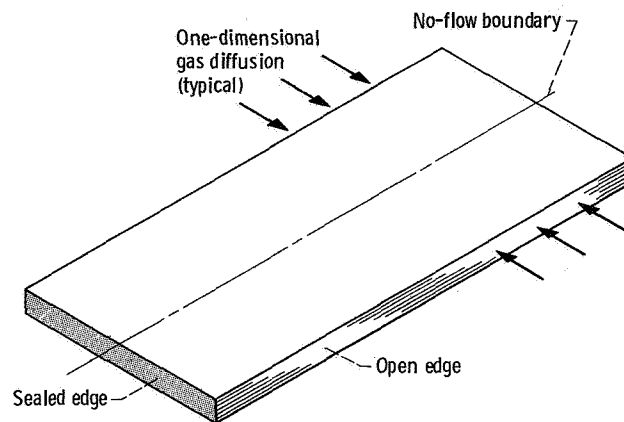
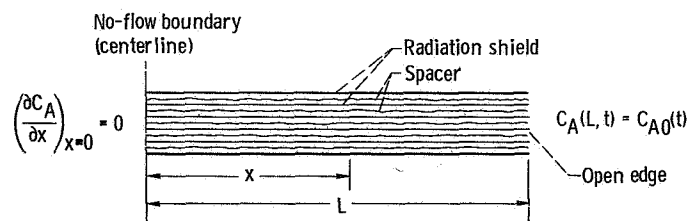


Figure 28. - Effect of uncovering grommets on gaseous nitrogen concentration within multilayer insulation (MLI) panel 60.3 centimeters from butt joint. Tests 2I, 2J, and 2L; horizontal orientation; MLI panel gaseous helium purge rate, 9.5 MLI panel volumes per hour (0.14 std m³/hr).



(a) Basic multilayer insulation panel.



(b) Analytical gas diffusion model.

Figure 29. - Analytical model for one-dimensional gas diffusion in a flat multilayer insulation panel.

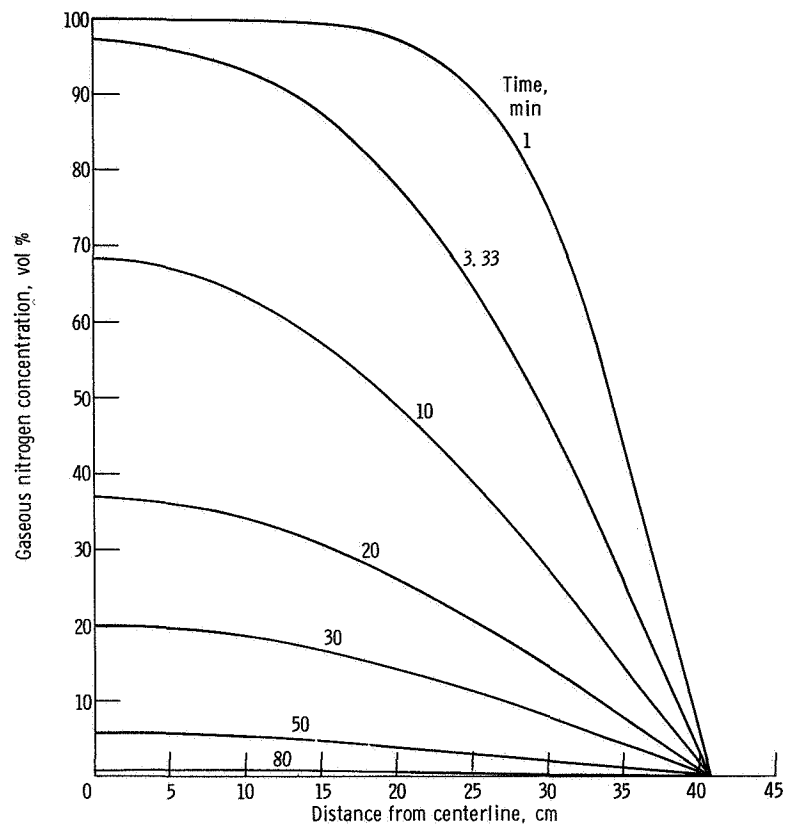


Figure 30. - Analytical prediction of gaseous nitrogen concentration within basic multilayer insulation (MLI) panel as a function of time for a step change to 100 percent gaseous helium at edge of panel (boundary condition).

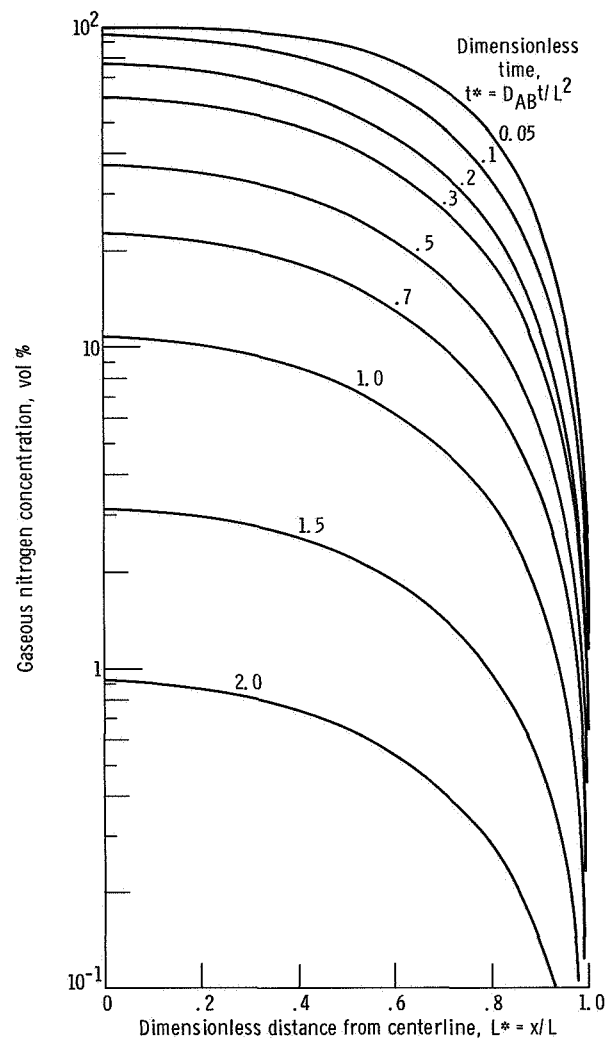


Figure 31. - Analytical prediction (in dimensionless form) of gaseous nitrogen concentration within basic multi-layer insulation panel for a step change to 100 percent gaseous helium at edge of panel (boundary condition).



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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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